PONTIFICIAE
ACADEMIAE
SCIENTIARVM
SCRIPTA VARIA

99

Science and the Future of Mankind

Science for Man and Man for Science

PROCEEDINGS

Working Group
12-14 November 1999

Jubilee Plenary Session
10-13 November 2000

VATICAN CITY
2001

SCIENCE AND THE FUTURE OF MANKIND

Science for Man and Man for Science

Address:
THE PONTIFICAL ACADEMY OF SCIENCES
CASINA PIO IV, 00120 VATICAN CITY

PONTIFICIAE ACADEMIAE SCIENTIARUM SCRIPTA VARIA

99

SCIENCE AND THE FUTURE OF MANKIND

Science for Man and Man for Science

the

PROCEEDINGS

of

the Preparatory Session
12-14 November 1999

and

the Jubilee Plenary Session
10-13 November 2000

EX AEDIBVS ACADEMICIS IN CIVITATE VATICANA

MMI

The opinions expressed with absolute freedom during the presentation of the papers of these two meetings, although published by the Academy, represent only the points of view of the participants and not those of the Academy.

ISBN 88 - 7761 - 075 - 1

PONTIFICIA ACADEMIA SCIENTIARVM
VATICAN CITY

CONTENTS

COMMEMORATION OF ACADEMICIANS

SELF-PRESENTATIONS OF THE NEW MEMBERS

THE PIUS XI GOLD MEDAL AWARD – SELF-PRESENTATIONS

SCIENTIFIC PAPERS

PART I: *Science for Man and Man for Science (Working Group)*

PART II: *Science and the Future of Mankind (Jubilee Session)*

PREFACE

This volume contains the proceedings of two meetings of the Pontifical Academy of Sciences: the working group of 12-14 November 1999 on 'science for man and man for science' and the Jubilee Plenary Session of 10-13 November 2000 on 'science and the future of mankind'. The two meetings dealt with very similar subjects, indeed the first was intended to prepare the ground for the second, and it is for this reason that it was decided to publish them in a single volume. Both these meetings addressed two topics which the Academy had been subjecting to debate for some time. On the one hand, there is the original relationship that the human being has with science, which, as the work of man, should always be at the service of human development. On the other, there is science, which, even when it deals with topics which are not specifically human has, and expresses, an idea of man, and this is something which we should strive to be aware of – that is to say: what does contemporary science say about the human being? One may think here, for example, of the important mind-body problem on which the Academy has produced more than one publication.

The first topic, 'science for man and man for science', was the subject of the working group of 12-14 November 1999. The first part of this topic, 'science for man', was examined in great detail by the Pontifical Academy of Sciences in the 1970s and 1980s and discussed at length by the recent World Conference on Science. In its final declaration on science and the use of scientific knowledge, this notion was expressed by that conference with the formula: science for knowledge; knowledge for progress, which included science for peace; science for development; and science in society and science for society. The Pontifical Academy of Sciences believes that we must explore the ways in which science can help in developing and promoting the specifically human dimension of man, society, and the environment. At the same time, the Academy believes that we should also discuss the ways in which, in contrary fashion, in certain situations, science can be responsible for a decline in the quality of life, as happens in particular in the case of damage done to the environment, the consequences of the invention and use of sophisticated weapons, etc. The second part of this topic, 'man for science', involved identifying the impact of recent scientific discoveries and advances on our vision of man, both directly and indirectly.

This question bore upon the topic addressed by the Jubilee Plenary Session of 10-13 November 2000: ‘science and the future of mankind’. With a strong interdisciplinary approach and through papers given by experts from different regions of the world, this meeting explored how science conditions the life of contemporary man. From physics to biology, and from the earth sciences to chemistry, leading scholars addressed themselves to the ways in which science is shaping and will shape the future of mankind. In addition, in the context of the Jubilee year 2000, the Pontifical Academy could not but refer to that ultimate horizon which begins on the outer frontiers of science. From philosophy to theology, from cosmology and biology to a new natural theology, from the Messianic ideal to the progress of science, and from the North to the South of the globe, the various speakers sought to illustrate the relationship between science and the deepest direction of man.

In covering these two topics, this volume thus presents a rather complete picture of the realities and the challenges which mankind now faces at the beginning of the third millennium. It does this in the belief that, as observed by the encyclical *Fides et Ratio*, every advance of science, wherever it may take place, does not close the horizon of transcendence to man, and that the fullness of faith leads man to knowledge of science, as is demonstrated by the fact that modern science was born during the Christian era with the assimilation of the message of freedom placed by Christ in the heart of man.

This preface would certainly not be complete without an expression of gratitude to the President, Prof. Nicola Cabibbo, the Council, and the Academicians and the experts who gave papers at, took part in, and thus made possible, these meetings. An expression of gratitude, also, to the fifty Academicians who took part in the closed session of the General Assembly of November 2000, at which it was decided to produce a study-document (published at the end of this volume) on the use of genetically modified food plants to combat hunger in the world. The Pontifical Academy of Sciences is also deeply grateful to the Holy Father John Paul II who not only follows and supports its activities with great interest and care, as is demonstrated by his Address to the Jubilee Plenary Session which is published in this volume, but also is convinced that today more than ever before a new alliance between Science and Faith can help to purify faith and open science to the salvation of man.

MARCELO SÁNCHEZ SORONDO,
Bishop-Chancellor of the Pontifical Academy of Sciences

ADDRESS TO THE HOLY FATHER

NICOLA CABIBBO

Holy Father,

This Audience that you have granted to the Pontifical Academy of Sciences on the occasion of the Plenary Session on 'Science and the Future of Mankind' offers an opportunity to cast our eyes back over the decades passed since its foundation by Pius XI in 1936. Pius XI wanted to renew the glorious Academy of the Lincei which at the beginning of the seventeenth century, during the age of the Renaissance, was the leading light of scientific endeavour.

During these years the Academy has followed two lines of research. The first has sought to evaluate and assess the rapid progress of scientific knowledge and its impact on the evolving concept of nature. Certain scientific ideas, which were speculative extrapolations a few decades ago, have since become well ascertained facts.

'Big Bang' cosmology, proposed in the thirties by our former President, Father Lemaître, is today confirmed by innumerable results, ranging from cosmic background radiation and its observed fluctuations, which beautifully mirror the birth of galaxies, to the relative abundance of chemical elements in the universe. The development of molecular biology has clarified the mechanisms underlying the evolution of living organisms, and has also provided the basis by which to establish a complete genealogy of life from humble bacteria to the higher organisms.

For many years the Academy has repeatedly been honoured by the keenly-felt interest Your Holiness has always shown towards these developments. During the same period the Academy has completed important studies, such as those on the determination of the state of death which proved crucial for clarifying the ethical status of organ transplants, and the preparatory studies on the Galileo case.

The second, and perhaps the more urgent, line of research in which our Academy has engaged looks at the consequences for mankind of the rapid development of scientific knowledge and the resulting swift increase in technical capabilities. Recently, in 'Fides et Ratio', you urged all scientists never to lose sight of the 'sapiential dimension', where technical prowess must be matched by respect for the ethical imperative to protect human life and dignity.

Over the years the Academy has met many times to discuss the difficulties and problems which third-world countries encounter in their development: food and agriculture, health, energy and water, industry and the dangers which derive from its often unsupervised development, and the ways in which the application of scientific knowledge can help to solve such difficulties and problems.

The Academy has also addressed itself to the dangers that the unwise use of technology can represent for our planet and mankind as a whole, but has at the same time considered the ways in which scientific progress can best be used to defend humanity against actual and potential dangers, both natural and man-made, and to meet its more urgent needs.

A high point in our activities was certainly represented by the solemn warning which the Academy issued in 1982 about the dangers of an unbridled race in the perfection and stockpiling of atomic weapons. I would like to recall an earlier example of this warning – in 1942 Pius XII warned of the impending danger of the development of nuclear weapons capable of massive destruction. His attention had been directed to this danger by one of the early members of our Academy, Max Planck, the discoverer of quantum physics.

This Plenary Session, and the preparatory meeting held last year, have acquired a special meaning from their being held at the same time as the Jubilee Year of the third millennium. The Academy, which this year has welcomed twelve new members – among whom four Nobel-prize winners – would like to take this opportunity to renew its special relationship with the Holy See. We will do so in the conviction that the far-seeing project of an Academy devoted to promoting and monitoring the advancement of science has proved fruitful in the past and remains fully valid as we face up to the challenges of the new millennium.

To this project, Holy Father, you have devoted attention and offered your encouragement during the course of your Pontificate, and we will do our best to be worthy of your beneficence over the coming years. Thank you.

ADDRESS OF THE HOLY FATHER JOHN PAUL II ON THE OCCASION OF THE JUBILEE PLENARY SESSION OF THE PONTIFICAL ACADEMY OF SCIENCES

Mr. President,
Distinguished Ladies and Gentlemen,

1. With joy I extend to you my cordial greetings on the occasion of the Plenary Session of your Academy, which, given the Jubilee context in which it is taking place, takes on special significance and value. I would like, first of all, to thank your President, Professor Nicola Cabibbo, for the kind words that he addressed to me on behalf of you all. I extend my keenly-felt expression of thanks to you all for this meeting and for the expert and valued contribution which you offer to the progress of scientific knowledge for the good of humanity.

Continuing, and almost completing, your deliberations of last year, you have dwelt over the last few days on the stimulating subject of 'science and the future of mankind'. I am happy to observe that in recent years your study-weeks and plenary assemblies have been dedicated in an increasingly explicit way to investigating that dimension of science which we could define as anthropological or humanistic. This important aspect of scientific research was also addressed on the occasion of the Jubilee of Scientists, celebrated in May, and, more recently, on the occasion of the Jubilee of University Teachers. I hope and wish that reflection on the anthropological contents of knowledge and the necessary rigour of scientific research can be developed in a meaningful way, thereby offering illuminating indications for the overall progress of man and society.

2. When one speaks about the humanistic dimension of science, thought is directed for the most part to the ethical responsibility of scientific research because of its consequences for man. The problem is real and has given rise to constant concern on the part of the Magisterium of the Church, especially during the second part of the twentieth century. But it is

clear that it would be reductive to limit reflection on the humanistic dimension of science to a mere reference to this concern. This could even lead some people to fear that a kind of 'humanistic control of science' is being envisaged, almost as though, on the assumption that there is a dialectical tension between these two spheres of knowledge, it was the task of the humanistic disciplines to guide and orientate in an external way the aspirations and the results of the natural sciences, directed as they are towards the planning of ever new research and extending its practical application.

From another point of view, analysis of the anthropological dimension of science raises above all else a precise set of epistemological questions and issues. That is to say, one wants to emphasise that the observer is always involved in the object that is observed. This is true not only in research into the extremely small, where the limits to knowledge due to this close involvement have been evident and have been discussed philosophically for a long time, but also in the most recent research into the extremely large, where the particular philosophical approach adopted by the scientist can influence in a significant way the description of the cosmos, when questions spring forth about everything, about the origins and the meaning of the universe itself.

At a more general level, as the history of science demonstrates to us rather well, both the formulation of a theory and the instinctive perception which has guided many discoveries often reveal themselves to be conditioned by philosophical, aesthetic and at times even religious and existential prior understandings which were already present in the subject. But in relation to these questions as well, the analysis of the anthropological dimension or the humanistic value of science bears upon only a specific aspect, within the more general epistemological question of the relationship between the subject and the object.

Lastly, reference is made to 'humanism in science' or 'scientific humanism' in order to emphasise the importance of an integrated and complete culture capable of overcoming the separation of the humanistic disciplines and the experimental-scientific disciplines. If this separation is certainly advantageous at the analytical and methodological stage of any given research, it is rather less justified and not without dangers at the stage of synthesis, when the subject asks himself about the deepest motivations of his 'doing research' and about the 'human' consequences of the newly acquired knowledge, both at a personal level and at a collective and social level.

3. But beyond these questions and issues, to speak about the humanistic dimension of science involves bringing to the fore an 'inner' or 'existen-

tial' aspect, so to speak, which profoundly involves the researcher and deserves special attention. When I spoke some years ago at UNESCO, I had the opportunity to recall that culture, and thus also scientific culture, possesses in the first instance a value which is 'contained within the subject itself' (cf. *Insegnamenti*, III/1 [1980] 1639-1640). Every scientist, through personal study and research, completes himself and his own humanity. You are authoritative witnesses to this. Each one of you, indeed, thinking of his own life and his own experience, could say that research has constructed and in a certain way has marked his personality. Scientific research constitutes for you, as it does for many, the way for the personal encounter with truth, and perhaps the privileged place for the encounter itself with God, the Creator of heaven and earth. Seen from this point of view, science shines forth in all its value as a good capable of motivating an existence, as a great experience of freedom for truth, as a fundamental work of service. Through it, each researcher feels that he is able himself to grow, and to help others to grow, in humanity.

Truth, freedom and responsibility are connected in the experience of the scientist. In setting out on his path of research, he understands that he must tread not only with the impartiality required by the objectivity of his method but also with the intellectual honesty, the responsibility, and I would say with a kind of 'reverence', which befit the human spirit in its drawing near to truth. For the scientist, to understand in an ever better way the particular reality of man in relation to the biological-physical processes of nature, to discover always new aspects of the cosmos, to know more about the location and the distribution of resources, the social and environmental dynamics, and the logic of progress and development, becomes translated into a duty *to serve more fully the whole of mankind*, to which he belongs. For this reason, the ethical and moral responsibilities connected to scientific research can be perceived as a requirement within science, because it is a fully human activity, but not as control, or worse, as an imposition which comes from outside. The man of science knows perfectly, from the point of view of his knowledge, that truth cannot be subject to negotiation, cannot be obscured or abandoned to free conventions or agreements between groups of power, societies, or States. Therefore, because of the ideal of service to truth, he feels a special responsibility in relation to the advancement of mankind, not understood in generic or ideal terms, but as the advancement of the whole man and of everything that is authentically human.

4. Science conceived in this way can encounter the Church without difficulty and engage in a fruitful dialogue with her, because it is precisely man

who is 'the primary and fundamental way for the Church' (*Redemptor Hominis,* 14). Science can then look with interest to biblical Revelation which unveils the ultimate meaning of the dignity of man, who is created in the image of God. It can above all meet Christ, the Son of God, the Word made flesh, the perfect Man. Man, when following him, also becomes more human (cf. *Gaudium et Spes*, 41).

Is it not perhaps this centrality of Christ that the Church is celebrating in the Great Jubilee of the year 2000? In upholding the uniqueness and centrality of God made Man, the Church feels that she is given a great responsibility – that of proposing divine Revelation, which, without in any way rejecting 'what is true and holy' in the various religions of mankind (cf. *Nostra Aetate,* 2), indicates Christ, 'the way, the truth, and the life' (Jn 14:6), as the mystery in which everything finds fullness and completion.

In Christ, the centre and culmination of history (cf. *Terzo Millennio Adveniente,* 9-10), is also contained the norm for the future of mankind. In Him, the Church recognises the ultimate conditions allowing scientific progress to be also real human progress. They are the conditions of charity and service, those which ensure that all men have an authentically human life, capable of rising up to the Absolute, opening up not only to the wonders of nature but also to the mystery of God.

5. Distinguished Ladies and Gentlemen! In presenting you with these reflections on the anthropological contents and the humanistic dimension of scientific activity, it is my heartfelt desire that the discussions and investigations of these days will produce much fruit for your academic and scientific endeavour. My hope and wish is that you can contribute, with wisdom and love, to the cultural and spiritual growth of peoples.

To this end, I invoke upon you the light and the strength of the Lord Jesus, real God and real Man, in whom are united the rigour of truth and the reasons of life. I am pleased to assure you of my prayers for you and your work, and I impart upon each of you my Apostolic Blessing, which I willingly extend to all those you hold dear.

THE PONTIFICAL ACADEMY OF SCIENCES

Working Group
on

SCIENCE FOR MAN AND MAN FOR SCIENCE

(12-14 November 1999)

Programme

Friday, 12 November 1999

9:10-9:20	General introduction (N. Cabibbo)
9:20-10:20	*World Conference on Science* (W. Arber)
10:20-11:00	Coffee break
11:00-11:50	*Technology between Science and Man* (P. Germain)
11:50-12:30	*The Future of Energy* (C. Rubbia)
12:30-13:00	*Spinning Fluids, Geomagnetism and the Earth's Deep Interior* (R. Hide)
13:00-15:00	Lunch
15:00-15:40	*The Mathematisation of Science* (L.A. Caffarelli)
15:40-16:20	*Mathematics: Recent Developments and Cultural Aspects* (Y.I. Manin)
16:20-16:50	Coffee break
16:50-17:40	*Science as Utopia* (J. Mittelstrass)
17:40-18:30	*Modern Research in Astronomy* (G.V. Coyne)

8:30-19:10	*The Role of Atmospheric Chemistry in Global Range Research with Emphasis on the Tropics: Research Needs* (P.J. CRUTZEN)

Saturday, 13 November 1999

9:10-10:00	*Which Economic System is Likely to Best Serve Human Societies? The Scientific Question* (E. MALINVAUD)
10:00-10:50	*Coping with Uncertainty: the Economics of Global Warming* (P.S. DASGUPTA)
10:50-11:10	Coffee break
11:10-12:00	*Global Sustainability and Social Justice* (P.H. RAVEN)
12:00-12:30	*Choice and Responsibility in Problems of Population* (B.M. COLOMBO)
12:30-13:10	*The Search for Man* (J. MARÍAS)
13:00-15:10	Lunch
15:10-15:50	*Sciences and Meaning: Science Faced with the Crisis of Meaning* (F. JACQUES)
15:50-16:30	*The Concept of Specificity for Vaccinations against Cancer, against Infectious and Autoimmune Diseases* (M. SELA)
16:30-17:00	Coffee break
17:00-17:40	*Society in the Face of Scientific and Technological Development: Risk, Decision, Responsibility* (A. BLANC-LAPIERRE)
17:40-18:30	*Challenges for the Agricultural Scientists* (T.-T. CHANG)
20:00-23:00	Dinner offered by Dr. R.M. Tay, Ambassador of the Republic of China to the Holy See, at the 'Mandarin Restaurant' in Rome.

Sunday, 14 November 1999

9:00-11:00	Discussion

LIST OF PARTICIPANTS

Prof. WERNER ARBER (Pontifical Academician)
University of Basel
Department of Microbiology – Biozentrum
Klingelbergstrasse 70
CH-4056 Basel
(Switzerland)

Prof. Mariano ARTIGAS
Universidad de Navarra
Facultad Eclesiástica de Filosofia
31080 Pamplona
(Spain)

Prof. Ugo BALDINI
Università di Padova
Facoltà di Scienze Politiche
Istituto di Studi Storici
Via del Santo, 28
I-35123 Padova
(Italy)

Prof. André BLANC-LAPIERRE (Pontifical Academician)
Académie des Sciences
23, quai de Conti
F-75270 Paris Cedex 06
(France)

Prof. Nicola CABIBBO (Pontifical Academician)
President, the Pontifical Academy of Sciences
Università degli Studi di Roma “La Sapienza”
Dipartimento di Fisica
Piazzale A. Moro, 5
I-00185 Roma
(Italy)

Prof. Luis A. CAFFARELLI (Pontifical Academician)
The University of Texas at Austin
Department of Mathematics – RLM 8.100
Austin, TX 78712-1082
(U.S.A.)

Prof. Te-Tzu CHANG (Pontifical Academician)
Lane 131 Alley 13 No. 2F/2
Sha-lun Road, Tamshui
Taipei Hsien, Taiwan 251
(Republic of China)

Prof. Bernardo M. COLOMBO (Pontifical Academician)
Università degli Studi di Padova
Dipartimento di Scienze Statistiche
Via S. Francesco, 33
I-35121 Padova
(Italy)

Rev. P. Georges M.M. COTTIER, O.P. (Pontifical Academician)
Teologo della Casa Pontificia
Palazzo Apostolico
V-00120 Vatican City

Rev. P. George V. COYNE, S.J. (Pontifical Academician)
Director, Specola Vaticana
V-00120 Vatican City

Prof. Paul J. CRUTZEN (Pontifical Academician)
Max Planck Institute for Chemistry
Department of Atmospheric Chemistry
P.O. Box 3060
D-55020 Mainz
(Federal Republic of Germany)

Prof. Partha S. DASGUPTA (Pontifical Academician of Social Sciences)
University of Cambridge
Faculty of Economics and Politics
Austin Robinson Building – Sidgwick Avenue
Cambridge CB3 9DD
(United Kingdom)

Dr. Mohamed Hussein Said EL-SADR, Ambassador
Ambassador of the Arab Republic of Egypt to the Holy See
Piazza della Città Leonina, 9
I-00193 Roma
(Italy)

Prof. Paul GERMAIN (Pontifical Academician)
Secrétarie Perpétuel honoraire
Académie des Sciences
23, quai de Conti
F-75006 Paris
(France)

Dr. Charles HARPER, Jr.
John Templeton Foundation
Radnor Corporate Center
100 Matsonford Road – Suite 100, Building #5
Radnor, PA 19087
(U.S.A.)

Prof. Raymond HIDE (Pontifical Academician)
University of Oxford
Departmet of Physics
Clarendon Laboratory
Parks Road
Oxford OX1 3PU
(United Kingdom)

Prof. Francis JACQUES
Université de Paris III (Sorbonne-Nouvelle)
17, rue le Verrier
F-75006 Paris
(France)

Prof. Vladimir I. KEILIS-BOROK (Pontifical Academician)
International Institute of Earthquake
Prediction Theory and Mathematical Geophsyics
Warshavskoye sh. 79, Kor 2
Moscow 113556
(Russia)

Prof. Stanislaw LOJASIEWICZ (Pontifical Academician)
Jagelonian University, Mathematical Institute
Reymonta 4
PL-30059 Krakow
(Poland)

Rev. P. Jean-Michel MALDAMÉ, O.P. (Pontifical Academician)
Institut Catholique de Toulouse
Faculté de Philosophie
31, rue de la Fonderie
F-31068 Toulouse Cedex
(France)

Prof. Edmond MALINVAUD (President of the Pontifical Academy of Social Sciences)
Centre de Recherche en Economie et Statistique (INSEE)
15, boulevard Gabriel Péri
F-92245 Malakoff Cedex
(France)

Prof. Félix Wa Kalenga MALU (Pontifical Academician)
Commissariat Général a L'Energie Atomique (C.G.E.A.)
Reactor Department
P.O. Box 868
Kinshasa / XI
(Republique Democratique du Congo)

Prof. Yuri I. MANIN (Pontifical Academician)
Max Planck Institute for Mathematics
Vivatsgasse, 7
D-53111 Bonn
(Federal Republic of Germany)

Prof. Julían MARÍAS
Accademico di Spagna
Vallehermoso 34
28015 Madrid
(Spain)

Prof. Jürgen MITTELSTRASS
Universität Konstanz
Philosophische Fakultät
Fachgruppe Philosophie
D-78457 Konstanz
(Federal Republic of Germany)

Dr. A.K. MUKHOPADHYAY
All India Institute of Medical Sciences
Department of Laboratory Medicine
P.O. Box 4938
New Delhi 110029
(India)

Prof. Crodowaldo PAVAN (Pontifical Academician)
Universidade de Sao Paulo
I.C.B. Microbiologia
P.O. Box 66208
Sao Paulo, S.P. 05389-970
(Brazil)

Prof. Giampietro PUPPI (Pontifical Academician)
Università degli Studi
Dipartimento di Fisica
Via Irnerio, 46
I-40126 Bologna
(Italy)

Prof. Alberto QUADRIO CURZIO
Dean, Facoltà di Scienze Politiche
Università Cattolica del Sacro Cuore
Largo A. Gemelli, 1
I-20123 Milano
(Italy)

Prof. Peter H. RAVEN (Pontifical Academician)
Director, Missouri Botanical Garden
P.O. Box 299
St. Louis, MO 63166-0299
(U.S.A.)

Prof. Carlo RUBBIA (Pontifical Academician)
President, Ente per le Nuove Tecnologie, L'Energia e L'Ambiente (E.N.E.A.)
Lungotevere Thaon di Revel, 76
I-00196 Roma
(Italy)

Rev. Msgr. Prof. Marcelo SÁNCHEZ SORONDO (Pontifical Academician)
Chancellor, the Pontifical Academy of Sciences
Libera Università Maria SS. Assunta
Via Pompeo Magno, 22
I-00192 Roma
(Italy)

Dr. Armen SARKISSIAN
Ambassador of the Republic of Armenia to the Holy See
Via dei Colli della Farnesina, 174
I-00194 Roma
(Italy)

Prof. Michael SELA (Pontifical Academician)
The Weizzmann Institute of Science
Department of Immunology
P.O. 26
Rehovot 76100
(Israel)

Prof. William SHEA
Université Louis Pasteur de Strasbourg
7, rue de l'Université
F-67000 Starsbourg
(France)

Prof. Joshua D. SILVER
University of Oxford
New College
Oxford OX1 3BN
(United Kingdom)

Prof. Jean STAUNE
Université Interdisciplinaire de Paris
29, rue Viala
F-75015 Paris
(France)

Prof. Giuseppe TOGNON
Libera Università Maria SS. Assunta
Via Pompeo Magno, 22
I-00192 Roma
(Italy)

Prof. Hans TUPPY (Pontifical Academician)
University of Vienna
Institute of Biochemistry
Dr. Bohr-Gasse 9,3.Stock
A-1030 Vienna
(Austria)

Prof. Anna-Teresa TYMIENIECKA
Rector, the World Institute for Advanced
Phenomenological Research and Learning
348 Payson Road
Belmont, MA 02478
(U.S.A.)

Prof. Miguel A. VIRASORO
Director, the Abdsus Salam International
Centre for Theoretical Physics
Strada Costiera, 11
I-34014 Trieste
(Italy)

Dr. Alberto J. VOLLMER HERRERA
Ambassador of Venezuela to the Holy See
Via Antonio Gramsci, 14
I-00186 Roma (Italy)

Dr. Christine VOLLMER
Pontificia Accademia per la Vita
V-00120 Vatican City

THE PONTIFICAL ACADEMY OF SCIENCES

Jubilee Plenary Session
on

SCIENCE AND THE FUTURE OF MANKIND

(10-13 November 2000)

Programme

Friday, 10 November

9:00-9:10	N. Cabibbo: *General Introduction*
9:10-9:50	*Commemorations of the Deceased Academicians:* Lichnerowicz André (11.12.98) *Mathematical Physics;* McConnell James Robert (13.2.99) *Theoretical Physics;* Herzberg Gerhard (3.3.99) *Nobel Laureate in Chemistry, 1971;* Chagas Carlos (16.2.00) *Biology and Biophysics;* Brück Hermann Alexander (4.3.00) *Astronomy*; Döbereiner Johanna (5.10.00) *Soil Microbiology*.
9:50-10:25	*Self-presentation of the New Academicians:* T.-T. Chang – C. Cohen-Tannoudji – R. Farina – N.M. Le Douarin – M.J. Molina – J.E. Murray – S. Pagano – F. Press – R. Vicuña – C.N. Yang – A.H. Zewail – A. Zichichi
10:25-11:00	C.N. Yang: *Quantization, Symmetry and Face Factors – Thematic Melodies of Twentieth-Century Theoretical Physics*
11:00-11:40	Coffee break
11:40-12:25	C. Cohen-Tannoudji: *Light and Matter*
12:25-13:00	E. Berti: *The Relationship between Science, Religion and Aristotelian Theology Today*
13:00-15:00	Lunch

CHAIRPERSON: W. Arber

15:00-15:50	A. Eschenmoser: *Design* versus *Selection in Chemistry and Beyond*
15:50-16:30	C.N.R. Rao: *Chemical Design of New Materials*
16:30-16:55	Coffee break
16:55-17:50	N.M. Le Douarin: *Developmental Biology: Novel Trends and Prospects*
17:50-18:30	G. Cottier: *Erreur, Correction, Réhabilitation et Pardon*

Saturday, 11 November

CHAIRPERSON: V.I. Keilis-Borok

9:00-10:00	C.H. Townes: *Parallelism and Ultimate Convergence of Science and Religion*
10:00-10:40	R. Swinburne: *Natural Theology in the Light of Modern Cosmology and Biology*
10:40-11:00	Coffee break
11:00-11:40	J.-M. Maldamé: *Messianisme et Science Moderne*
11:40-12:20	W.E. Carroll: *Creation and Science*
12:20-13:30	W.J. Singer: *The Evolution of Consciousness*
13:30-15:10	Lunch

CHAIRPERSON: A. Eschenmoser

15:10-15:40	F. Press: *Earth Sciences: Remarkable Scientific Progress, Extraordinary Opportunity for Human Betterment*
15:40-16:30	M.J. Molina: *Global Change and the Antarctic Ozone Hole*
16:30-16:50	Coffee break

CHAIRPERSON: N. Cabibbo

16:50-17:30	M. Moshinsky: *Science for Man and Man for Science: a View from the Third World*
17:30-18:00	R.L. Mössbauer: *Physics in the Past Century and in the Future*
18:00-18:30	S.L. Jaki: *The Christological Background of the Origin of Newton's First Law*
20.00-21.30	Dinner offered by H.E. Raymond Tai, Ambassador of the Republic of China to the Holy See (Hotel Columbus, Via della Conciliazione, 33)

Sunday, 12 November

8:30-16:30	Visit to the 'Ville Pontificie' of Castel Gandolfo
10:00-10:10	'Pius XI Medal' Award – *Self-Presentations* (Prof. Mark M. Davis, 1996 – Prof. Gillian P. Bates and Prof. Stephen W. Davies, 1998)
10:10-12:00	Discussions
12:00-13:00	Visit to the gardens of Castel Gandolfo
13:00	Lunch

Monday, 13 November

CHAIRPERSON: L.A. Caffarelli

9:00-9:40	V.I. Keilis-Borok: *Colliding Cascades: a Model for Prediction of Critical Transitions*
9:40-10:20	A.H. Zewail: *Science for the Have-nots*
10:30-10:50	Coffee break
10:50-13:00	Papal Audience
13:00-15:00	Lunch

CHAIRPERSON: N. Cabibbo

15:00-15:40	Minoru Oda: *Why and how Physicists are Interested in the Brain and in the Mind*
15:40-16:30	V.C. Rubin: *Imaging the Universe: Past and Future*
16:30-17:00	Coffee break
17:00-17:50	R. Omnés: *Some Advances in the Interpretation of Quantum Mechanics and Consequences in Philosophy*
17:50-18:30	P. Poupard: *Christ and Science*
19:00	Holy Mass (in memory of Prof. Carlos Chagas)

LIST OF PARTICIPANTS

ACADEMICIANS

ARBER Werner
BLANC-LAPIERRE André
CABIBBO Nicola
CAFFARELLI Luís A.
CHANG Te-Tzu
COHEN-TANNOUDJI Claude
COLOMBO Bernardo M.
COTTIER Georges M.M.
COYNE George V.
ESCHENMOSER Albert
FARINA Raffaele
GERMAIN Paul
JAKI Stanley L.
KEILIS-BOROK Vladimir I.
LE DOUARIN Nicole M.
LEVI-MONTALCINI Rita
LOJASIEWICZ Stanislaw
MALDAMÉ Jean-Michel
MANIN Yuri I.
MENON M.G.K.
MOLINA Mario J.
MOSHINSKY Marcos
MÖSSBAUER Rudolf L.
MURADIAN Rudolf
MURRAY Joseph E.
ODA Minoru
PAGANO Sergio
PAVAN Crodowaldo

PRESS Frank
RAO Chintamani N.R.
RAVEN Peter
REES Martin J.
RICH Alexander
RUBIN Vera C.
SÁNCHEZ SORONDO Marcelo
SELA Michael
SINGER Wolf J.
SZCZEKLIK Andrew
THIRRING Walter
TOWNES Charles H.
TUPPY Hans
VICUÑA Rafael
YANG Chen Ning
ZEWAIL Ahmed H.
ZICHICHI Antonino

INVITED EXPERTS

Prof. Enrico BERTI
Università degli Studi di Padova
Dipartimento di Filosofia
Piazza Capitaniato, 3
I-35139 Padova
(Italy)

Prof. William E. CARROLL
Cornell College
Department of History
600 First Street West
Mount Vernon, IA 52314-1098
(U.S.A.)

Prof. Roland OMNÉS
Université de Paris-Sud, Centre D'Orsay
Laboratoire de Physique Théorique
Unité Mixte de Recherche n° 8627
Bâtiment 210
F-91405 Orsay Cedex
(France)

H.E. Paul Card. POUPARD, President
Pontificio Consiglio della Cultura
Palazzo S. Calisto
V-00120 Vatican City

Prof. Richard G. SWINBURNE
Oriel College
Oxford OX1 4EW
(United Kingdom)

OBSERVERS

Prof. Gillian BATES (Pius XI Medal 1998)
University of London
King's College – Division of Medical and Molecular Genetics
Guy's, King's and St. Thomas' School of Medicine
8th Floor, Guy's Tower
London SE1 9BT
(United Kingdom)

Fr. Rémy Bergeret, O.P.
Couvent Saint-Thomas d'Aquin
Impasse Lacordaire
F-31078 Toulouse Cedex 4
(France)

Prof. Stephen W. DAVIES (Pius XI Medal 1998)
University College London
Department of Anatomy and Developmental Biology
Gower Street
London WC1E 6BT
(United Kingdom)

Prof. Mark M. DAVIS (Pius XI Medal 1996)
Stanford University School of Medicine
Department of Microbiology and Immunology
Howard Hughes Medical Institute
Stanford, CA 94305-5323
(U.S.A.)

Prof. Anna GIARDINI GUIDONI
Università degli Studi di Roma “La Sapienza”
Dipartimento di Chimica
Piazzale Aldo Moro, 5
I-00185 ROMA
(Italy)

Prof. Francis JACQUES
Université de Paris III (Sorbonne-Nouvelle)
17, rue le Verrier
F-75006 Paris
(France)

Prof. Jürgen MITTELSTRASS
Universität Konstanz
Philosophische Fakultät – Fachgruppe Philosophie – Postfach 5560 D 15
D-78434 Konstanz
(Federal Republic of Germany)

Dr. Charles SEIFE
Science Magazine
1200 New York Avenue, NW
Washington, D.C. 20008
(U.S.A.)

Prof. Anna-Teresa TYMIENIECKA
Rector, The World Institute for Advanced
Phenomenological Research and Learing
348 Payson Road
Belmont, MA 02478
(U.S.A.)

COMMEMORATION OF ACADEMICIANS

ANDRÉ LICHNEROWICZ

André Lichnerowicz was elected to our Pontifical Academy of Sciences in 1981. He was a very active member and attended nearly all the plenary sessions. He was with us in November 1998, indeed very present, making very fruitful remarks during the discussions on many scientific papers and also during our business session.

He was born on 21 January 1915 in Bourbon l'Archambault, France. His parents were brilliant teachers: he had a literary father who was secretary general of the Alliance Française and a mathematician mother from the Ecole Normale Supérieure of Sèvres. He was a student of the Ecole Normale Supérieure in 1933, doctor in sciences in 1939 with a thesis on general relativity, and Maître de Conférences in mechanics at the Faculté des Sciences of Strasbourg, where he published his first treatise 'Algèbre et Analyse Linéaire' in which he presented theories which were rather poorly taught during that period in France. The book became immediately famous.

In 1949 André Lichnérowicz was appointed to a position in the Sorbonne, at the Faculté des Sciences de Paris, where he established a new diploma on mathematical methods in physics (MMP), and in 1952 he was appointed to a chair in mathematical physics at the Collège de France. He taught there until 1986 and he remained scientifically active until his death on 11 December 1998. His is a wonderful and exceptional curriculum.

André Lichnerowicz was an immensely cultured man, interested throughout his life in the most varied problems, whether scientific, philosophical, educational, artistic, social or religious in character. He was a great intellectual, always ready and happy to discuss issues and questions with people. He had a great desire to communicate his ideas. Talking with him was always fruitful. He understood rapidly what you wanted to say and often saw quickly the weakness of your position.

He showed an active interest in the role of sciences, and particularly of mathematics, in the life of the community. He was not only an active participant, but also one of the most important organisers during the fifties of national conferences, which were open to a broad public including people belonging to all political formations and whose object was to emphasise the need for a serious reform of the universities and our research system. (Caen 1956-Amiens 1960). He was one of the twelve scientists who belonged to the first Comité Consultatif de la Recherche Scientifique et Technique created by de Gaulle immediately after becoming President of the country in the late 1950s.

It should also be recorded that from December 1966 to June 1973 he was the president of the famous ministerial commission on the teaching of mathematics, which everybody called the 'Lichnerowicz commission'. The fundamental idea of Lichnerowicz was that to ensure the harmonious development of our society it was necessary to give our people a strong scientific culture and within such culture a prominent place was given to mathematical culture. The project was ambitious. Many Institutes de Recherche sur l'Enseignement Mathématique were created. Many are still in operation. They have done excellent work and it is thanks to them that the mathematical education of young people in France is still quite good. But most of the hopes and expectations of Lichnerowicz have not yet been realised. The commission met formidable obstacles which still remain and which have to be tackled if we want to bring to mathematics teaching the qualities dreamed of by Lichnerowicz. These obstacles were sociological inertia, administrative and corporate rigidity, the narrow-mindedness of many mathematicians, and the mathematical illiteracy of most of the population.

The mathematical production of Lichnerowicz was fantastic. He published more than 350 papers and books and he had a great many students of his own. One should emphasise that he was one of the first professors in France to introduce a closer kind of direction of theses. Instead of expecting to be told "Here is a thesis topic. Come back and see me when you have found a new result", the student knew that he could go to see him very often. Lichnerowicz considered himself responsible for anyone who was or had been his student. That explains why he had so many of them. He provided them with unfailing support, particularly when they had difficulties in their professional or private lives. Lichnerowicz knew how to choose for each one a thesis topic appropriate to that person's tastes and capacities, a topic which would permit him – encouraged and helped as much as necessary – to obtain the sought-for diploma. This remarkable diversity of choices offered by Lichnerowicz to his students came from the variety of his own interests.

It is time now to say a few words about his personal scientific achievements. This is an impossible task. Fortunately, five former students of Lichnerowicz who are all first-class mathematicians, Marcel Berger, Jean-Pierre Bourgignon, Yvonne Choquet-Bruhat, Charles-Michel Marle and André Revuz, have written a joint paper in the 'Gazette des Mathematiciens' (n. 32, 1999, pp. 90-109) which has been published in various forms in the Notices of the AMS (vol. 4, n. 11, pp. 1387-1396).

Lichnerowicz was at one and the same time a geometrician and a physicist. He was fascinated by mechanics and more generally by the mathematical representation of the physical universe. Let us note only briefly the most important domains in which Lichnerowicz worked and published.

Lichnerowicz was interested in many facets of differential geometry. The relation between curvature and topology is a very natural topic in Riemannian geometry. Many papers were devoted to what may be called roughly the Bochner heritage, in particular Leplacian calculations. Lichnerowicz demonstrated his ability to make difficult calculations in a very clever way and to find formulae that described deeply fundamental properties. He was also a master of the Kähler domain, motivated in particular by the long-standing question of Elie Cartan. Among the questions in which he obtained important results were those connected with the classification of Riemannian manifolds and the use of their holonomy groups in order to obtain the answer.

Another broad field of research of Lichnerowicz was general relativity. His thesis belonged to this field. In 1939 he provided a global differential geometric point of view of general relativity. Later on, he made explicit in the appropriate general context the necessary and sufficient conditions for a metric to be a global solution of the Einsteinian equations. Lichnerowicz's methodology has been used in the construction of numerous models. He was the first person to obtain a coherent mathematical formulation of the theory of relativity. In 1970 he gave courses on hydrodynamics and relativistic magneto-hydrodynamics including thermodynamics, and obtained in particular beautiful results on shock waves. On must also cite his works on gravitational radiation, spinor fields, and the quantisation of fields on curved space-time.

On should also mention another set of important contributions to symplectic geometry and to the various manifolds which can be useful in providing the basis of convenient formulations of physical situations: Poisson manifolds, Jacobi manifolds and their geometry. A new field of research which he introduced in about 1970 was the theory of the deformation of the algebra of functions on a manifold. With his co-workers, Lichnerowicz showed that the formal deformations of the associate algebra of differential functions of a sympletic – or Poisson – manifold offered a method for the quantisation of classical Hamiltonian systems.

To close this rapid look at the works of Lichnerowicz, I would like to say that all those who attended lectures or courses given by André Lichnerowicz would agree with the opinion of Charles-Michel Marle: 'I admire his exceptional virtuosity in calculation and the perfect arrangement of difficult proofs which he always explains in a complete manner. The most admirable of his mathematical skills is the depth of his vision which permitted him to abstract key concepts of today's and tomorrow's mathematics'.

I would like to add a few observations of a more personal character to conclude this commemoration of André Lichnerowicz as a mathematician and his radiance within human culture and the human city.

I borrow the first from Jean-Pierre Bourguignon. With his wife, who was born in Peru and taught Spanish in a Paris high school, he formed an extremely interesting blend of different sensitivities. The two of them were sharp, remarkably cultivated, and open to many cultures. Nothing escaped their notice. An after-conference dinner with them (she often accompanied him on his scientific trips) was certainly an enriching experience.

The second concerns his faith. He was a believing Catholic. I may mention here two places where he expressed his thoughts. One is a paper in a collective volume entitled 'Le savant et la foi' (edited by Jean Delumeau-Flammarion and published in 1989). Its title is 'Mathématicien et chrétien' (pages 187-204). The other is an interview in a special issue of the magazine 'Sciences et Avenir' entitled 'Dieu et la Science'. As was always the case with Lichnerowicz, his thought was very clearly expressed.

Paul Germain

JAMES ROBERT MCCONNELL

James Robert McConnell was one of the most distinguished of Irish scientists of his epoch and the doyen of Irish theoretical physicists. He entered University College Dublin in 1932 and graduated four years later with a Master's Degree in mathematics which he obtained with first honors. During those studies he came under the influence of the distinguished mathematical physicist and Pontifical Academician A.W. Conway who aroused in McConnell an interest in relativity and quantum theory. From that moment Conway became his mentor.

McConnell gained the degree of Doctor of Mathematical Sciences in 1941 at the University of Rome "La Sapienza." Despite wartime difficulties, he managed to return to Dublin in 1942 and with Conway's support he was appointed Scholar at the School of Theoretical Physics of the newly founded Dublin Institute for Advanced Studies where he came under the influence and inspiration of the world-renowned physicists Erwin Schrödinger and Walter Heitler. His original researches were in nonlinear electromagnetic theory but he soon began a detailed study of the theory of the negative proton, or antiproton, whose existence was not confirmed until 1955.

In 1945 McConnell was appointed Professor of Mathematical Physics at St. Patrick's College, Maynooth, where he continued his researches into the theory of fundamental particles. Following his appointment in 1968 to a senior professorship in the School of Theoretical Physics of the Dublin Institute, his research interests changed and he took up the study of the theory of rotational Brownian motion. He was elected to membership in the Royal Irish Academy in 1949 and was granted a Doctor of Science degree by the National University of Ireland.

From 1969 to 1972 McConnell was Director of the School of Theoretical Physics of the Dublin Institute and he was secretary of the Royal Irish Academy from 1967 to 1972. He was a founding member of the European Physical Society and served on its Council from 1969 to 1971. In recognition of his contributions to science he was awarded the Boyle Medal by the Royal Dublin Society in 1986. He was appointed to the Pontifical Academy of Sciences in 1990 by Pope John Paul II. As many of us who knew him at this Academy can testify, James McConnell was a friendly, unassuming and generous man, who was full of vitality and who had an infectious enthusiasm for all that he undertook to accomplish.

George V. Coyne, S.J.

GERHARD HERZBERG

Dr. Herzberg was born in Germany and during his doctoral and post-doctoral studies in Germany he was associated with such eminent scientists as Max Born and James Franck. His early interests were in astronomy and later in atomic and molecular physics. In spite of his extraordinary accomplishments at a young age, Dr. Herzberg had to leave Germany and move to North America in 1935. He went to Canada where he wrote his classic books on spectroscopy, and later moved to the Yerkes Laboratory at the University of Chicago. After a brief stay in Chicago he went back to the National Research Council of Canada with which he was identified for the rest of his career.

Dr. Herzberg was clearly the father of modern molecular spectroscopy. The entire world of spectroscopy considered him its champion and statesman. Even spectroscopists who did not know him personally considered him their teacher because of his classic papers and books, which had a great impact. His contributions to molecular spectroscopy, in particular to the spectroscopy of molecules of astronomical interest, were truly outstanding.

Dr. Herzberg received many honours and was a member of several Academies including the Royal Society and the US National Academy of Sciences. He was awarded the Nobel prize in chemistry in 1971.

C.N.R. Rao

CARLOS CHAGAS FILHO

Prof. Carlos Chagas Filho, former President of the Pontifical Academy of Sciences, died on 16 February 2000, in Rio de Janeiro, Brazil, at the age of eighty-nine. As his name suggests, he was the son of the famous Brazilian medical doctor, Carlos Chagas, who at the beginning of the twentieth century discovered the causes of an important tropical illness which subsequently bore his name – 'Chagas Disease'.

Chagas Filho graduated in medicine in 1935 with great success, and from the outset of his career he directed his activities to scientific research. Chagas Filho was a privileged person: from his parents he received an excellent genetic background, an extraordinary cultural inheritance, and, to complete his success in life, he had a very happy marriage. His wife, Anah, contributed a great deal to his social life and his cultural activities.

In spite of these advantages, Chagas Filho's life was not easy. Having a famous father in the same professional area meant that he had to be very demanding with himself in a methodical and constant way. In this way he was able to achieve success in scientific production and advancement in several cultural areas at both a national and an international level.

He began his scientific career as a student of medicine at the Institute

Oswaldo Cruz in Rio de Janeiro, Brazil. After graduating in medicine he also obtained degrees in physics and mathematics. He began his research with work on the electric fish, *Electrophorus electricus*. With great success, in collaboration with colleagues and mainly with disciples and students, a series of more than one hundred important articles were published by Chagas in specialist reviews with an international circulation.

In 1936 he was appointed Full Professor of Biophysics at the Faculty of Medicine of the University of Rio de Janeiro. In 1945 he inaugurated the Institute of Biophysics at that university, an institution which was able to produce scientific knowledge and researchers of a high level. A few years later this Institute received international recognition as a Centre of Excellency, a status that it has maintained until today.

He promoted academic and educational activities of high level in Brazil and abroad. He received a Doctorate in Science from the University of Paris (1946); was President of the United Nations Committee on the Study of the Effects of Atomic Radiation (1956-62); was General Secretary of the Conference of the United Nations for the Application of Science and of Technology in Special Development, Geneva (1962-66); and was the Brazilian Permanent Ambassador at UNESCO, Paris, France (1966-70). We could mention about fifty other similar activities to be found in his curriculum. For example, he was a member of fifty-three scientific societies or Academies of Sciences. The list of decorations, medals, prizes and honorary titles that were granted to him is long indeed.

Of great importance in Chagas Filho's activities was the efficient way in which he carried out the command tasks with which he was entrusted. To give some examples mention may be made of:

a) his magnificent performance as the Director of the Institute of Biophysics, an Institute recognised internationally as much for its scientific production as for the training of outstanding researchers;

b) his presidency of the United Nations Committee on the Study of the Effects of Atomic Radiation, which under his leadership produced a series of publications of great importance and relevance at the time. These were fundamental in the drawing up of conventions and international agreements on the use of the nuclear energy;

c) how Prof. Federico Mayor, General Secretary of UNESCO, who from 1966 to 1970 worked in that institution under the leadership of Chagas, affirmed that: 'Don Carlos had the extraordinary quality of convincing his collaborators that what they did at that moment was the most important thing in their lives';

d) the magnificent performance of Chagas as President of the Pontifical Academy of Sciences. This is summed up by what he said when receiving the position, in 1972, from Pope Paul VI: “What I want in this function is very clear. I will try to change the Academy from a body of great prestige into one of great action also”. This intention was expressed in important action. There was the revision of the Galileo case, an act which received universal approval, and was, without doubt, one of the landmarks of the Chagas presidency. Another important initiative, which had the support of the Academicians, Victor Weisskopf and Louis Leprince-Ringuet, was the campaign in 1981 against atomic arsenals and the production of atomic weapons. This wielded great influence on the resolutions which were subsequently passed by the United Nations. Acting in harmony with that campaign, Pope John Paul II sent letters to the governments of Washington, Moscow, Paris and London – the countries that had the atomic bomb – in which he asked them to receive a delegation from the Pontifical Academy of Sciences which would explain to them the dangers of possible nuclear conflicts for the future of the human species. These initiatives played an important role in the peace resolutions that were later approved by the governments of those countries and by the UN;

e) the excellent publications of the proceedings of the plenary sessions held during the Chagas presidency, especially those on ‘the Origin of the Universe, ‘the Origin of Life’, and ‘the Origin of Man’. These demonstrated the mutual understanding which existed between the Catholic Church and Science, something which was always propagated with enthusiasm by Carlos Chagas Filho.

Chagas Filho believed in what he was doing. That is demonstrated in an article written by Darcy Fontoura de Almeida, one of his former-students. He related how Chagas was an ‘academic professor par excellence who performed his duties even in a wheel chair until December of 1999, attending the Institute of Biophysics, tracking a post-graduate course which was highly appreciated by the students’.

From another former-student, Antônio Paes de Carvalho, we have the statement: ‘The owner of a special intelligence, Chagas prevailed by reason in all the forums in which he had the opportunity to act, inside and outside of the country. In science, so demanding in its methodology, Chagas’s contribution was marked by the creativity of his ideas, his heady hypotheses, and the rigidity and the patience with which he knew how to lead his more immediate collaborators. We could not find a better paradigm of dignity, of intelligence, and of love for one’s neighbour and of the wisdom of life’.

Chagas Filho possessed an extraordinary series of human qualities. One of the most evident was his firm and constant propensity to do what was good.

Of Chagas Filho, whom I knew for sixty years and with whom I shared numerous contacts and collaborations, I have the most valuable and honorable memories, besides an enormous admiration. He was really a great human being.

C. Pavan

HERMANN ALEXANDER BRÜCK

Hermann Brück was a member of the Pontifical Academy for forty-five years. In the course of his long, cosmopolitan life he contributed greatly to astronomy – especially to the modernisation of observatories and the improvement of observational techniques.

He was born in 1905, the only child of Hermann Heinrich Brück, an officer of the Prussian army killed in 1914 at the Battle of Lodz. He attended the Kaiserin Augusta Gymnasium in Charlottenburg. His mother would have preferred him to become a lawyer, but his uncle, a distinguished bacteriologist, argued that science could also be a respectable profession.

He started his university career in Kiel; but he found no inspiration there, and moved on after one semester. He was far more fortunate in Munich, where he completed his first degree. He was taught by the legendary, charismatic physicist Arnold Sommerfeld, in the exciting years when quantum mechanics was being formulated – indeed, he attended the colloquium where Heisenberg first presented the famous 'uncertainty principle'. He obtained his doctorate in 1928 for work on the physics of crystals. Sommerfeld then encouraged him to read Arthur Eddington's recently-published book on 'The Internal Constitution of the Stars'. Brück moved to an astronomical post at Potsdam, and within a few years became a lecturer at the University of Berlin, where luminaries like Max von Laue, Erwin Schrödinger and Albert Einstein were on the faculty.

Brück left Germany abruptly in 1936, when Nazi aggression worsened. He came for a year to the Vatican Observatory in Castel Gandolfo. This was a formative period both scientifically and spiritually. He was received into the Roman Catholic Church by Romano Guardini and Johannes Pinsk, two of the most distinguished theologians of the age: his intense commitment to the Church continued throughout his long life.

His next move was to the Cambridge Observatories in England, in 1937. After war broke out, he was interned as an enemy alien, but within six months Eddington secured his release, and he returned to a post of greater responsibility in Cambridge. But in 1947 he received a personal invitation from Eamon de Valera, then Prime Minister of the Irish Republic, to become Director of the Dunsink Observatory and Professor of Astronomy at the new Dublin Institute for Advanced Studies, where he joined his friend Erwin Schrödinger, who had been invited to be Professor of Theoretical Physics.

After a successful decade in Ireland he moved again. On the personal initiative of Sir Edward Appleton, then Vice-Chancellor of Edinburgh University, he was invited to become Director of the Royal Observatory in Edinburgh, and Astronomer Royal for Scotland. Brück's personal scientific interests were in the physics of the interstellar medium, questions of stellar evolution and the formation of stars from diffuse interstellar material. But his impact was wider because he had a natural authority, and proved an effective innovator. During his tenure, the observatory staff numbers expanded from eight to more than a hundred. He fostered the work of Fellgett on automatic plate scanning machines, and that of Reddish on new telescopes. He thereby prepared the way for the pioneering Cosmos High-Speed Measuring Instrument, the 'Schmidt telescope' in Australia, as well as the UK Infra-Red Telescope and the James Clerk Maxwell Radio Telescope in Hawaii.

He championed the establishment of observing stations in climates better than that of Great Britain and was a prime advocate of a UK Northern Hemisphere Observatory in the Canary Islands. The Edinburgh Observatory still goes from strength to strength as a major astronomical centre, and its standing owes a great deal to Brück's far-sighted leadership.

Brück continued living near Edinburgh with his second wife, Mary, throughout his long and active retirement. (His first wife, Irma, had died in 1950.) Mary, who survives him, has herself a fine record as a professional astronomer. Hermann and Mary produced a highly readable biography of the eccentric nineteenth-century astronomer Charles Piazzi Smyth – one of Brück's predecessors in Edinburgh who pioneered stereoscopic photography but gained embarrassing notoriety through his obsession with the numerology of the Great Pyramid. The Brücks also wrote a history of astronomy in Edinburgh, tracing its emergence back to the Scottish enlightenment.

The Pontifical Academy meant a great deal to Hermann Brück. He was proud to have been elected when Georges Lemaître was President, and to have known him well. He gained special satisfaction from the memorable Study-Week which he organised on the theme 'Astrophysical Cosmology'. This took place in 1981 – a time when new links between cosmology and physics were being perceived. The meeting gathered together an outstanding group of scientists; the proceedings, beautifully edited, came out promptly and were widely influential.

He served on the Academy's Council for twenty years. And he lived long enough to be honoured for his services: on his ninetieth birthday Pope John Paul II appointed him Knight Grand Cross of the Order of St. Gregory the Great.

Those of us who were privileged to know Hermann Brück will cherish the memory of a dedicated scientist whose courteous dignity overlay a brilliant intellect and a firm faith.

Martin J. Rees

JOHANNA DÖBEREINER

Johanna Döbereiner (28/11/1924-5/10/2000) was born in Aussig, in Czechoslovakia, and lived with her family for some years in Prague, the city where her father, Paul Kubelka, was a teacher at the German University. As a youth her life was afflicted and very difficult.

At the age of seventeen, in the middle of the Second World War, she was forced to separate from her family and for a period of about four years had only occasional encounters with her parents and grandparents. She worked in several places in a broad range of activities. To begin with, she took care of children in government-sponsored colonies inside Czechoslovakia, and later she lived and worked on farms, milking cows, distributing natural fertilisers in the farms and orchards, and helping in the weeding of crops. Through these activities she was able to sustain and help her grandparents' survival.

In 1945, as a consequence of the war, together with her grandparents, she was expelled from Czechoslovakia, from which she went to Germany where she continued working in farms until 1947, in which year she was offered a place in the School of Agriculture of Munich, where, in 1950, she graduated as an agricultural engineer.

Her mother, after enduring great deprivations and even internment in concentration camps, died and was buried under a changed name, Anna, instead of Margareth Kubelka. Her widowed father and her brother Werner, with the help of foreign teachers based in Brazil and the Brazilian citizen Mário Pinto, managed in 1948 to migrate to Brazil. In 1950, Johanna, already married to Jürg Döbereiner, a University colleague, emigrated with him to Brazil. In 1956 she became a naturalized Brazilian citizen.

In 1951, in Rio de Janeiro, she was employed by the Department of Agriculture and began her work on nitrogen fixing bacteria, an area that she knew only from references to it in her agronomy course. Even without a specialised adviser, she believed so much in the importance of the subject that initially, with very few resources and a great deal of perseverance, she achieved, with students and collaborators, excellent progress in this field. Her work was abundant in practical results and publications that went beyond the borders of Brazil to receive wide international recognition.

Her work on soy-bean culture, involving the selection of bacteria which fix nitrogen from the air and pass it on through symbiosis to the plant, led to the substitution, with great advantages, of the application of artificial nitrogen fertilisers. With collaborators she produced the most efficient culture of soy-bean existent today, something which has proved to have great economical and ecological value. By planting in Brazilian soil, without the use of artificial nitrogen fertiliser, she obtained a productivity comparable to the North American cultures, which depended on artificial fertilisers and were the largest soy-bean producers per unit area in the world. These cultures are now generating great profits (hundreds of millions of dollars) for Brazilian and Argentinian farmers, and this latter group uses the same technology as that elaborated by the group of researchers led by J. Döbereiner.

In terms of the ecological aspects of soy-bean culture, it has been demonstrated in works published by the Ecological Society of America that artificial nitrogen fertiliser, used in agriculture throughout the world, is an important polluting agent of the terrestrial aquatic system and is already contaminating the sea systems. The use of nitrogen fixing bacteria is without doubt the most important alternative that exists to achieve a solution to this problem.

Of no less importance are some other achievements of the work of Döbereiner's group, in particular the discovery of several new species of nitrogen fixing bacteria associated with cereals, grasses and other non-leguminous species.

In contrast to the classical concept of rhizosphere associations, these bacteria colonise the roots, stems and leaves of wheat, rice, maize, sorghum, and a great number of other wild plant species.

Some of these species of bacteria are obligate endophytes and do not survive in the soil, and their transmission occurs within seeds or stem cuttings.

These discoveries by Döbereiner now exert a very important influence on agricultural processes involving the legume plants mentioned above and are expected to make a no less important contribution to the agriculture of non-legume plants and also to the conservation of biodiversity around the world. Their importance in the transition to sustainability is more than evident.

This outstanding scientist received several prizes, including the Bernard Houssay Prize of the OEA (1979); the Prize for Science of UNESCO (1989); the Mexican Prize for Science and Technology (1992), and others. She belonged to the Brazilian Academy of Sciences (1977), to the Pontifical Academy of Sciences (1978), and was a Founding Member of the Third World Academy of Sciences (1981).

The list of her publications includes over 370 papers published in international scientific journals. In a survey carried out in 1997 by the ‘ Folha de São Paulo’, a major Brazilian daily newspaper, she was classified as the most cited (Citation Index International) of Brazilian female scientists and belonged to the top 10% of both male and female cited scientists.

Apart from losing a great researcher, the Brazilian scientific community, and especially myself, have lost a very dear and esteemed friend whose memory will be cherished by us all.

C. Pavan

SELF-PRESENTATIONS

TE-TZU CHANG

I am a Chinese national and my name, if Romanised, reads as Chang Te-Tzu. For the convenience of colleagues and friends, I generally use the abbreviated form, T.T. Chang. You are welcome to call me 'T.T.'

I completed my education at the college level in China. My graduate studies were then pursued in the USA.

My major area of research is plant genetics and its application to crop improvement, germplasm conservation, and crop evolution.

During my professional career I have served two institutions: the Sino-U.S. Joint Commission on Rural Reconstruction (JCRR) in Taiwan and the International Rice Research Institute (IRRI) in the Philippines. Both institutions have earned world-wide fame for enhancing the livelihood of underprivileged farmers and low-income consumers through the achievement of increased food production and more equitable distribution.

My contributions at the level of research and technology transfer have been:

1) the introduction of the potent semidwarfing gene in Taiwan's lane races into tropical rice. This greatly raised yield potential and led to the 'Green Revolution' in rice; and

2) the conservation of the diminishing land races, thus reducing the perils of genetic uniformity in improved cultivars. Through international collaboration we were able to save endangered gene-pools and preserve their seeds at the IRRI. Many land races and their wild relatives are no longer found in their old habitats. I also shared my expertise and experience in seed storage with national and international agricultural research centres by helping China, India, Taiwan and others in constructing modern genebanks.

In recognition of these activities, many awards and honours have been bestowed on me. Nevertheless, I highly value my membership of the

Pontifical Academy of Sciences. Actually, I began my collaboration with this Academy in 1998 with the Study-Week on the 'Food Needs of the Developing World in the Early Twenty-First Century'. Its proceedings have just been published.

I am both honoured and pleased to be present at this Assembly and to join many eminent scientists in discussing the role of science and the future of mankind.

Thank you.

CLAUDE COHEN-TANNOUDJI

I was born on April 1, 1933, in Constantine, Algeria, which was then part of France. My family, originally from Tangiers, settled in Tunisia and then in Algeria after having fled Spain during the Inquisition. In fact, my name, Cohen-Tannoudji, means simply the Cohen family from Tangiers.

I completed my primary and secondary school education in Algiers and left Algiers for Paris in 1953, before the war in Algeria and the stormy period that preceded independence.

I came to Paris because I was admitted to the Ecole Normale Supérieure. The four years I spent at this school were a unique experience. Being fascinated by Alfred Kastler's lectures in physics, I decided to join his group to do my "diploma" work and I think that what I learned during that period was essential for my subsequent research work. After the final "Agregation" examination, I left Ecole Normale as a student. In 1960, I returned as a researcher and submitted my Ph.D. in December 1962. Shortly after, I was appointed to a position at the University of Paris.

Understanding atom-photon interactions was one of the main goals of our research group and led us to develop a new approach, the so-called "dressed atom approach", which turned out to be very useful in providing new insights into atom-photon interactions.

Another important event in my scientific life was my appointment as a Professor at the Collège de France in 1973. In the early 1980s, I chose to lecture on radiative forces, a field which was very new at that time and I formed a new experimental research group on laser cooling and trapping with Alain Aspect, Jean Dalibard, and Christophe Salomon. We began to investigate new cooling mechanisms suggested by the dressed atom approach. Our work was devoted to the understanding of the mechanical effects of light and to the investigation of possible applications of these effects.

In 1997, I was awarded the Nobel Prize in Physics jointly with Bill Phillips and Steven Chu for the development of methods to cool and trap atoms with laser light. This research field has considerably expanded during the last few years and I will try to describe a few recent developments and applications in the paper which follows this self-presentation.

RAFFAELE FARINA, S.D.B.

As the Prefect of the Vatican Library I was appointed a 'perdurante munere' member of the Pontifical Academy of Sciences on 24 May 1997.

I obtained my doctorate in ecclesiastical history at the Gregorian University of Rome. I was Professor of the History of the Ancient Church at the Salesian Pontifical University of Rome from 1965 to1997 and was Rector of the same university from 1977 to 1983 and from 1992 to 1997. I was also for a period President of the Committee of the Pontifical Universities of Rome. Within the Roman Curia I was Under-Secretary of the Pontifical Council for Culture from 1986 to 1992 and Secretary of the Pontifical Committee for Historical Sciences from 1980 to 1992.

NICOLE LE DOUARIN

Nicole Le Douarin started her research carrier in 1958 under the sponsorship of Prof. Etienne Wolff who was the Director of the Institut d'Embryologie Expérimentale et de Tératologie du Centre National de la Recherche Scientifique et du Collège de France in Nogent-sur-Marne. For two years she worked in the laboratory only part time since, from 1954, she was teaching in a lycee. She became full time researcher in 1960 and submitted a thesis for the "Doctorat d'Etat" in 1964. Her thesis was entitled "Etude expérimentale de l'organogenèse du tube digestif et du foie chez l'embryon de Poulet". She was appointed as Maitre de Conférences first in the Faculté des Sciences of Clermont-Ferrand in 1965-1966, then in the Faculté des Sciences of Nantes where she became Professor in 1971. She was responsible for teaching developmental biology and had the opportunity of setting up a Developmental Biology Research Unit with the support of the CNRS.

In 1975, when Prof. Etienne Wolff retired, she was invited to take over the Directorship of the Institut d'Embryologie du Collège de France et du CNRS at Nogent-sur-Marne. She was appointed Professor at the Collège de France in the Chair of "Embryologie cellulaire et moléculaire" in 1989, a position that she occupied until September 2000. She was elected a member of the French Académie des Sciences in 1982, of the American Academy of Arts and Sciences in 1984, of the National Academy of the United States America in 1989, and of the Royal Society of the United Kingdom in 1990. She received the Kyoto Prize in Advanced Technology in 1986, the Gold Medal of the CNRS in 1986, the Jeantet Price for Medicine in 1990, the Luisa Gross Horwitz Price of Columbia University in New York in 1993, and the Grand Prix de la Fondation pour la Rercherche Médicale Française in 1999. She has been elected as the "Secrétaire Perpétuelle" of the Académie des Sciences de l'Institut de France from January 1st, 2001 and she continues to do research part time at the Institut d'Embryologie Cellulaire et Moléculaire du Collège de France et du CNRS.

MARIO J. MOLINA

I was born in Mexico City. I obtained a degree in chemical engineering from the Universidad Nacional Autónoma de México (UNAM) in 1965, and a Ph.D. in physical chemistry from the University of California, Berkeley in 1972. I came to MIT in 1989 with a joint appointment in the Department of Earth, Atmospheric and Planetary Sciences and the Department of Chemistry, and became MIT Institute Professor in 1997. Prior to joining MIT, I held teaching and research positions at UNAM, at the University of California, Irvine, and at the Jet Propulsion Laboratory of the California Institute of Technology.

My main work involves laboratory studies of chemical systems of importance in the atmosphere. In particular, I have conducted research on the chemistry of the stratospheric ozone layer and its susceptibility to human-made perturbations. In 1974 I published together with F. S. Rowland an article in the British magazine 'Nature' describing our research on the threat to the ozone layer from chlorofluorocarbon (CFC) gases that were being used as propellants in spray cans, as refrigerants, as solvents, etc. As a consequence, the production of these gases was eventually banned in developed countries.

More recently I have also been involved with the chemistry of the lower atmosphere, pursuing interdisciplinary work on urban and regional air pollution issues and working with colleagues from several disciplines on the problem of rapidly growing cities with severe air quality problems. I am currently heading a collaborative research and education program based at MIT aimed at addressing the complex and interrelated environmental issues spawned by the world's rapidly growing mega-cities and their impact on the global environment. Mexico City serves as the initial case-study for this program's research and educational activities.

JOSEPH E. MURRAY

Surgery as Science – Surgery as Humanism

My professional life has been primarily spent caring for patients. Teaching and research have also been prominent.

After graduating from medical school during World War II, I was randomly assigned to a military hospital in the United States that cared for battle casualties from the European, African and Pacific theatres.

Treating a young aviator burned in a crash flying from Burma to China (when the U.S. was helping China in the war against Japan) gave me my first experience in using tissues from a dead person as a life-saving measure. This experience directed my professional activities.

After three years of Army surgery, I joined a group of physicians studying kidney transplantation at Harvard Medical School. Working in the surgical research lab, I developed techniques of transplantation in mice, rabbits and dogs. In 1954, we performed the world's first successful human kidney transplant between identical twins. Five years later, in 1959, we successfully transplanted a human kidney from a cadaver. Our team consisted of clinicians and basic scientists working toward a common goal. For this, I was recognized by the Nobel Committee and awarded the Nobel Prize in Medicine in 1990.

Transplantation of other organs by other investigators rapidly followed (i.e. liver, heart, pancreas, lung, heart/lung, and intestines). By the early

1970's, transplantation was being performed worldwide. At that time, I decided to move away from transplantation and, instead, concentrated on my original surgical passion – reconstructive surgery. This included craniofacial problems (congenital, traumatic or neo-plastic) in children and adults. Just as organ transplantation required knowledge of biochemistry and immunology, craniofacial problems required interaction with basic genetics and embryology.

During my surgical career of over 50 years, surgery has evolved from excision, reconstruction and transplantation to inductive surgery. These advances required the understanding and contributions of both basic scientists and clinical scientists, confirming Pasteur's dictum, “There is only one science. Basic and clinical science are closely joined as the trunk of a tree is to its branches.”

SERGIO PAGANO

Né à Gênes le 6 novembre 1948, il est entré dans la Congrégation des Barnabites en 1966. Il a étudié la philosophie et la théologie à Rome, où il a été ordonné prêtre en 1978. La même année il obtient la maîtrise en théologie avec spécialisation en Liturgie, le diplôme de Paléographe Archiviste auprès de l'École Vaticane de Paléographie, Diplomatique et Archivistique, puis il est nommé “Scriptor” des Archives Secrètes Vaticanes. Actuellement, il est professeur de diplomatique pontificale dans cette École. Membre de l'Académie San Carlo de Milan, représentant des Archives Secrètes au Comité International d'Archivistique, consulteur historique de la Congrégation pour les Causes des Saints depuis mai 1985, il est nommé Vice Préfet des Archives Secrètes Vaticanes par Jean-Paul II le 30 janvier 1995. Quelques jours plus tard, il reçoit la charge de Vice Directeur de l'École Vaticane de Paléographie, Diplomatique et Archivistique. Depuis 1989, il est Supérieur du Centre d'Études historiques des Pères Barnabites de Rome. Le 7 janvier 1997, il est nommé Préfet des Archives Secrètes Vaticanes et Directeur de l'École Vaticane de Paléographie, Diplomatique et Archivistique. Il est membre de droit “perdurante munere” de l'Académie Pontificale des Sciences et du Comité Pontifical des Sciences Historiques. Depuis Mars 2000, il est membre correspondant des *Monumenta Germaniae Historica* et depuis juillet 2000, il est membre de la Société Romaine d'Histoire de la Patrie.

FRANK PRESS

I have found it challenging and rejuvenating to change positions every 5 to 10 years. In this way I have had the opportunity to serve as teacher and researcher at three great research universities – Columbia, Caltech, and MIT. The face to face discourse with students and faculty, the laboratory, library, and computational resources, the air of imminent discovery at these places provide an ideal environment for a scientist to be creative and fulfilled.

After some 25 years so occupied, I received a call from President Jimmy Carter to become his Science Adviser. Although the work during the four year term was taxing and stressful, not particularly enjoyable, and ended my life as a bench scientist it was an experience not to be missed. Other than learning on the job, there is no way to prepare oneself for the turbulent world of politics and its intersection with science and technology (which includes most issues faced by a nation's chief executive). I had to prove myself all over again in a new environment where credentials and publications meant little and contributing to the success of a political administration meant everything. Perhaps I had it a bit easier than other Science Advisers because President Carter was trained as an engineer, was conversant in science, and most importantly, I agreed with his goals.

In 1981 I was elected to the Presidency of the U.S. National Academy of Sciences (NAS) and served for 12 years. I took less interest in the honorific aspects of the Academy than in its unique role as one of the most influential advisory bodies to any government. I was well prepared for this position because of my earlier academic and government position. Although advising the government as president of a private organization is not the same as being on site in the White House, I am proud of the many ways in which the NAS helped the government to address issues ranging from the AIDS epidemic, to arms control, science budgets and industrial productivity.

As I look back on my career (hopefully, it is not yet over), I am proud of my discoveries as a scientist in partnership with my graduate students and colleagues. But most of all I take particular pleasure in my undergraduate textbooks *Earth* and *Understanding Earth*, co-authored with Professor Raymond Siever of Harvard, which from 1974 to 2000 have introduced a million or so students to the planet on which they live.

RAFAEL VICUÑA

First of all, I would like to express my profound gratitude to His Holiness John Paul II for appointing me a new member of the Pontifical Academy of Sciences. I receive this appointment with the greatest honour and I wish to declare my commitment, dedication and faithfulness to the aims of this highly prestigious institution.

I would also like to thank the members of the Academy for their support and I confirm my intention to actively contribute with the highest interest and motivation to those activities where the Academy may feel my input would be helpful.

Science represents one of the most prominent endeavours of humankind. For several centuries it has demonstrated that it is the most reliable tool that exists for unlocking the secrets of nature. From this perspective, it represents one of the fundamental supports of our cultural progress. At the same time, science has led to the development of new technologies which have had a dramatic impact on agriculture, industry, and medicine, as well as on everyday life, thereby bringing about the social progress of humanity.

Nowadays science advances so fast that we are increasingly confronted with scenarios that could not have been foreseen some years ago. Unfortunately, we do not seem to dedicate enough time to reflecting about the implications of the new discoveries, or even about the new capabilities, acquired by scientists in their laboratories. For example, the ability to manipulate cells and genes has opened up new horizons in agriculture and human reproduction. At times, some of these advances challenge our consciences and provoke dilemmas – we are faced with what we technically able to do *versus* doing what are we morally obliged to do. Therefore, institutions such as this Academy, which are devoted to deep reflection about the consequences of new knowledge, are more essential than ever in the provision of guidelines to the scientific community and society as a whole.

I will now say a few words about my academic career in the hope that this may help you to envisage how I might better serve this Academy. I have been attached to science ever since I finished high school thirty-four years ago. This has been not an easy engagement, since scientific research has very seldom been considered a worthwhile activity in Latin American countries. However, I strongly believe that scientific research is necessary to reach both intellectual autonomy and economic progress. Guided by this conviction, throughout this period I have been involved in various activities directed towards the strengthening of science in Chile. At the national level, I have participated several times in committees appointed by the government to discuss science programmes. I have also frequently served as an advisor to Congress in the analysis of legislation involving scientific issues. At the Pontifical Catholic University of Chile, the place where I work full time, I have served as dean of research and as vice-president for academic affairs, being responsible for the co-ordination of the research activities of our sixteen different Faculties. In the accomplishment of these duties I have gained some experience in the drawing up and administration of science policies.

With respect to the research fields that I have explored, during my Ph.D. studies in New York I worked on DNA replication in bacteria, which I continued to do for some years after my return to Santiago in 1978. Thereafter, I moved to the realm of thermophilic bacteria, being attracted by the amazing capability of these micro-organisms to thrive at temperatures around 80 ºC. My work encompassed the characterisation of some extrachromosomal DNA elements and also some enzymes involved in the metabolism of DNA in thermophilic bacteria. Fifteen years ago, after sabbatical leave supported by a Guggenheim fellowship in Madison, Wisconsin, I switched to my present field of interest, which is the biodegradation of lignin. Lignin is the second most abundant deposit of organic carbon in the biosphere and therefore its metabolism is a key component of the carbon cycle on earth. This macromolecule is closely associated with cellulose in the plant cell wall, providing plant tissues with mechanical strength and protecting them against microbial attack. Lignin is an insoluble polymer with a highly irregular structure, properties that make its biodegradation a very special biochemical process. My laboratory is approaching this fascinating problem by studying the ligninolytic system of a fungus which is particularly aggressive towards lignin in natural environments. We are characterising the enzymes that attack the polymer and studying both the structure and expression of the genes encoding them. Although our research can be considered as basic, it has some biotechnological connotations. One of its main applications is in the pulp and paper industry, the major process of which involves the removal of lignin from the wood and thus the release of the cellulose fibres. We have already worked with local companies with the end result of making their processes more efficient and environment-friendly.

Although, as I have just mentioned, my research in the laboratory deals with lignin biodegradation, I also manage to find the time to follow other subjects with great enthusiasm. One of them is the origin of life on earth. I had the privilege of attending a meeting on this subject which was held in Trieste last September. I also have a special interest in the subject of human evolution, which occupies much of my social reading. In addition, the Human Genome Project and its ethical and social implications have also commanded a great deal of my attention, especially during the current year.

Once again, I sincerely thank you all for your support and I restate my intention to dedicate my best efforts to serving the Pontifical Academy of Sciences with loyalty and responsibility.

CHEN NING YANG

I am Chen Ning Yang. I was born in China and went to the United States of America in 1945 to engage in post-graduate studies. After my Ph.D. at the University of Chicago, I spent seventeen years at the Institute for Advanced Study in Princeton and then joined the State University at Stony Brook where I was a professor for thirty-four years until my retirement one and a half years ago. I am now Distinguished Professor-at-Large at the Chinese University of Hong Kong. I am delighted to have been elected a member of the Pontifical Academy, in particular because my teacher, the great Enrico Fermi, was a professor in Rome and created modern physics research in Italy during his period in Rome.

AHMED H. ZEWAIL

On the banks of the Nile, the Rosetta Branch, I lived an enjoyable childhood. I was born in Egypt in Damanhour, the “City of Horous”, only 60 km from Alexandria. In retrospect, it is remarkable that my childhood origins were flanked by two great places – Rosetta, the city where the famous Stone was discovered, and Alexandria, the home of ancient learning.

I graduated from the University of Alexandria in 1967 with a B.S. degree, and shortly thereafter, in 8 months, with a Master’s degree. From the University of Pennsylvania in Philadelphia, USA, I received my Ph.D. degree, and at the University of California at Berkeley I completed two years of a postdoctoral fellowship. In 1976, I joined the faculty of the California Institute of Technology (Caltech) and I am currently the Linus

Pauling Chair Professor of Chemistry and Professor of Physics, and the Director of the NSF Laboratory for Molecular Sciences.

At Caltech, our research efforts have been devoted to developments of ultrafast lasers and electrons for studies of molecular dynamics with atomic-scale resolution. In the field of femtochemistry, developed by the Caltech group, and for which the 1999 Nobel Prize in Chemistry was awarded, the focus is on the fundamental femtosecond processes in chemistry and in related fields of physics and biology.

I have had the fortune of a wonderful family and the friendship of my wife, Dr. Dema Faham, who is here today. Currently we live in San Marino, California. Two of my children, Maha and Amani, are doing well in science and have graduated from Caltech and Berkeley, respectively. The two younger sons, Nabeel and Hani, have not yet reached this stage of college education, but the trajectory is clear! My scientific family over the past 20 years consists of some 150 postdoctoral research fellows, graduate students and visiting associates.

It is a pleasure to be inducted into this distinguished and historic academy.

ANTONINO ZICHICHI

My field of activity is subnuclear physics and is directed towards what is termed ‘the Standard Model’. This is the greatest synthesis of all times in understanding the basic Logic of Nature. Some major issues in subnuclear physics have attracted my interest. The following five points have been my contribution – during these four decades – to the building up of the Standard Model.

1. *The Third Lepton*

The problem of divergences in electro-weak interactions and the third lepton. Physics results are finite: why then do theoretical calculations, for example in Quantum Electro-Dynamics (QED), give rise to divergent quantities? High precision measurements in QED and in weak interactions attracted my interest. In fact, for example, the contributions of virtual weak processes in the elementary properties of the muon should produce divergent results. The cure for divergences was called, by theorists, renormalization. My career started with the first high precision measurements of the muon electromagnetic and weak basic properties, i.e. its anomalous magnetic moment (measured with ± 5 x 10^{-3} accuracy), and its weak charge (measured with ± 5 x 10^{-4} accuracy). The invention of new technologies for the detection of electrons and muons allowed me to start searching for a new lepton and to make a series of high precision QED tests. This activity culminated in the discovery by others of the third lepton (now called *t*) to which I have devoted ten years of my life.

2. *Matter-Antimatter Symmetry*

The violation of the symmetry operators (C, P, T, CP) and Matter-Antimatter Symmetry. I was very much intrigued by the great crisis arising from the discovery that the basic invariance laws (charge conjugation C, parity P, time reversal T) were not valid in some elementary processes. Together with the successes of the S-matrix and the proliferation of 'elementary' particles, the powerful formalism called Relativistic Quantum Field Theory (RQFT) appeared to be in trouble. These were the years when the RQFTs were only Abelian and no one was able to understand the nature of the strong forces. The discovery of CP breaking gave a new impetus to the search for the first example of nuclear antimatter: in fact the antideuteron had been searched for and found not to be produced at the 10^{-7} level. The order of magnitude of its production rate was unknown and finally found to be 10^{-8}. This level of detection was reached by my group thanks to the construction, at CERN, of the most intensive negative beam and of the most precise time-of-flight detector.

3. *Mesons Mixings*

The mixing in the pseudoscalar and vector mesons: the physics of Instantons. Another field thoroughly investigated by me is the mixing properties of the pseudoscalar and of the vector mesons, realized through the study of their rare decay modes. This could be accomplished thanks to the invention of a new detector, the neutron missing mass spectrometer. The physics issues could probably be synthetized in terms of the U(1) problem. In other words, why do the vector mesons not mix while the pseudoscalar mesons mix so much? This issue found – after many decades – a satisfactory answer when G. 't Hooft discovered how Instantons interact with the Dirac sea.

4. *Effective Energy*

The non-Abelian nature of the Interaction describing quarks, gluons and Effective Energy. Another puzzle to me was the enormous variety of multihadronic final states produced in strong, electromagnetic and weak interactions. Why are these final states all different? This appeared to be in contrast with the order of magnitude reduction in the number of mesons and baryons obtained, first with the eightfold way by Gell-Mann and Ne'eman and then with the quark proposal by Gell-Mann and Zweig. The discovery of Scaling at SLAC and the non-existence of quarks found by us at CERN using the ISR was finally understood in terms of quarks, gluons, and their non-Abelian interaction. With the advent of quarks and gluons, the puzzle became even more intriguing since the multihadronic final states had to have the same origin. The introduction of the new quantity, 'Effective Energy', allowed the discovery of the Universality Features in the multihadronic final states produced in strong, electromagnetic and weak interaction, thus solving the puzzle. It is remarkable that the quantitative QCD description of 'Effective Energy' is still missing, since it is a non-perturbative QCD effect.

5. *The Supersymmetry Threshold and its Problems*

As early as in 1979, I pointed out the relevance of this new degree of freedom for the convergence of the three gauge couplings. More than a decade later (1991), I realised that a serious effort was needed to put order and rigour into this field where unjustified claims on the Supersymmetry threshold became very popular despite their total lack of validity. For example, no one had ever computed the effect of the Evolution of the Gaugino Masses (EGM), not only on the convergence of the gauge couplings but, and more importantly, on the Supersymmetry threshold. The EGM effect brought down the Supersymmetry threshold by nearly three orders of magnitude.

A Note Concerning Projects and Technological Developments

My physics interests made me very much concerned about the future of subnuclear physics. This concern lies at the origin of my activity devoted to the implementation of new projects: the Erice Centre for the implementation of a genuine scientific culture; the Gran Sasso project, now the largest and most powerful underground laboratory in the world; the LEP-white-book which allowed this great European venture to overcome the many difficulties that had blocked its implementation for many years; the HERA collider, now successfully running; the roots of LHC (the new CERN collider) i.e. the 5 metre diameter for the LEP tunnel, and the LAA-R&D project, implemented to find the original detector technologies needed for the new colliders.

THE PIUS XI GOLD MEDAL AWARD

MARK M. DAVIS

Summary of Scientific Activity

I received my first exposure to serious laboratory work in synthetic organic chemistry in the laboratory of P.Y. Johnson as an undergraduate at Johns Hopkins University. In my last year, I was exposed to the mysteries of DNA chemistry by Michael Beer in the Biophysics department and I believe it was this (and having read "The Double Helix" a few years earlier) that inclined me towards working with this substance over the next twentysome years. As a graduate student at the California Institute of Technology, starting in 1974, I had the good fortune to work with DNA and RNA in two separate laboratories – first with Eric Davidson on hybridization analysis and "gene counting" strategies and then with Leroy Hood in using molecular cloning techniques to isolate and characterize rearrangements in immunoglobulin heavy chain genes. In 1980 I finished my Ph.D. and began working with William Paul at the National Institutes of Health (NIH). As work with antibody genes was winding down I thought that it would be interesting to combine what could be done with nucleic acid hybridization with the search for interesting genes in the immune system. This could be done by exhaustively hybridizing complementary DNA (cDNA) from one messenger RNA population with RNA from another. Previously, this had only been attempted with very different types of cells and tissues (liver versus kidney etc.) and large differences in gene expression had been seen, equivalent to thousands of different genes. From the natural history of lymphocytes, however, it seemed that they shared a similar origin and morphology such that I thought that T and B cells might differ by only a few genes, making the isolation of these relatively easy. After a few months of work at NIH, I was able to show that T and B cells indeed shared 98% of their gene expression and thus only 100-200 genes were expressed in one and not the other. With tremendous support and encouragement from Dr. Paul, I built up a small laboratory at NIH and set out to use these findings to isolate important genes in the immune system, particularly the T cell receptor for antigen, the equivalent of the antibody molecule for T lymphocytes. In 1983, we were successful in isolating the first of what later turned out to be four T cell receptor genes, just at the time that my wife, Yueh-hsiu Chien, also a scientist and I moved to take a faculty position at Stanford. We published the first T cell receptor paper in early 1984, in a dead heat with Tak Mak who had the human equivalent, and later that same year, mostly through the efforts of Chien, we published a paper describing the second chain of the heterodimer, this time in a photo-finish with Susumu Tonagawa, who had joined the fray.

Since the mid-eighties, my work has gradually shifted its focus from nucleic acid chemistry and characterization, to protein structure and biochemistry, cell biology and even to medical issues involving T lymphocytes. In this first area we were able to demonstrate direct T cell receptor binding to its peptide/MHC ligands and to link the strength of binding to the density of cell-surface clustering (with Michael Dustin). I also became curious about the high degree of sequence diversity in the center of the T cell receptor molecules and we were able to show that this region (the CDR3 loops) is the driving force behind peptide specificity. More recently we have also shown this to be true with immunoglobulins. An unexpected byproduct of our biochemical efforts was the realization that while T cell receptor binding was very weak in the micromolar range, it was nonetheless highly specific. This suggested that labeled multimers of peptide/MHC might be good “tags” for T cells with interesting specificities. After a few false starts, we made “tetramers” of peptide/MHC and these are able to stain T cells of just about any degree of specificity. This technique is becoming quite useful for clinical applications, allowing physicians to “follow” specific T cells responses to viral, cancer or autoimmune antigens quickly and easily.

More recently, we have used this approach to show that while tumor specific T cells do arise, sometimes in large numbers in patients with Melanoma, they seem almost completely non-functional compared with T cells of other specificities in the same patients.

The major interest in the lab currently is to follow the fate of labeled membrane proteins on live T cells during the recognition process, in order to discern the underlying chemistry. Interesting facts have emerged from this work about the nature of co-stimulation and the formation of what has been called “the immunological synapse”.

GILLIAN PATRICIA BATES

Summary of Scientific Activity

I first started to work on Huntington's disease (HD) in 1987 when I became a postdoctoral fellow in Hans Lehrachs' research group at the Imperial Cancer Research Fund in London. The HD gene had been mapped to the short arm of chromosome 4 three years previously by Jim Gusella. In order to isolate the gene itself, a collaborative group of scientists had been brought together by Dr. Nancy Wexler, President of the Hereditary Disease Foundation (HDF). This included six research groups in the USA and UK headed by Jim Gusella, Hans Lehrach, David Housman, John Wasmuth, Francis Collins and Peter Harper. Over the next six years we worked together to generate the necessary resources and develop the required technology to pinpoint the HD gene. This was an extraordinary training. Hans' laboratory was a leading light in developing technologies for both the positional cloning of genes and also the genome project. The HDF provided the opportunity to interact regularly in an informal setting with a group of extremely talented and gifted scientists. The collaborative group published the identification of the HD gene in 1993. It was found that the only difference between the DNA sequence of this gene in people that do not develop HD and those that become affected is the length of a repeated DNA sequence (CAGCAGCAG), very close to the beginning of the gene.

At the beginning of 1994, I became a Senior Lecturer at what is now the GKT School of Medicine, King's College and initiated my independent research programme. An understanding of the HD mutation made it possible for the first time to generate a mouse model of HD. This was extremely important, as an accurate mouse model would allow us to uncover the very early molecular events in the disease course and to test possible therapies. Initially, I focussed my work in this direction and we published the first mouse model of HD in 1996. One of these transgenic lines, known as R6/2 has an early age of onset and has proved to be particularly useful as it has been possible to carry out an extensive characterisation of these mice in a very short time. Dr. Stephen Davies carried out a neuropathological analysis of these mouse brains and made the first major insight that arose from their study. He found that the transgene protein (made from the HD mutation that we had inserted into the mouse DNA) formed aggregates in the nuclei of nerve cells (neuronal intranuclear inclusions) in the transgenic mouse brains. The significance of these structures was not immediately apparent, as protein deposits had never been described in

Huntington's disease. However, since their identification in the mice, polyglutamine aggregates have been widely reported in HD post mortem patient brains. Max Perutz in Cambridge, UK and Erich Wanker, working with Hans Lehrach at the Max Planck Institute for Molecular Genetics in Berlin showed that these fibres have a cross-β-sheet structure more commonly known as amyloid.

For the past three and a half years, the R6/2 mice have been distributed to the research community either by my own lab or by the Jackson Laboratory in the USA. There are already around forty publications describing research that has been conducted on these mice by many groups. Insights into the early molecular stages of HD are arising. Polyglutamine aggregates form very early in some brain regions, before the onset of symptoms. Work initiated with Jang Ho Cha and Anne Young and MGH, Boston, showed that selective genes, many known to be important for nerve cell function, are turned down early in the transgenic mouse brains. Finally, the mice have been used for testing pharmaceutical compounds and two drugs are already entering the early stages of clinical trials in the UK and USA. The mouse model has revolutionised our knowledge of this disease and in the space of only four years is already beginning to have an impact on the treatment of HD.

STEPHEN WHITWORTH DAVIES

Research Interests

My laboratory has a long standing interest in molecular mechanisms of transcriptional regulation in the striatum following neuronal injury

I am currently focussing on the mechanism of neurodegeneration in Huntington's disease and other diseases caused by trinucleotide repeat expansions. These studies are in collaboration with Dr. Gillian Bates (UMDS). Current research projects are: immunocytochemical characterisation of neuropathological changes in Huntington's disease, post-mortem brain and transgenic mouse models of HD (Barbara Cozens and Elizabeth Slavik-Smith), ultrastructural and biochemical characterisation of *in vitro* and *in vivo* fibrous aggregates of Huntington's disease (Aysha Raza), transcriptional regulation in transgenic mouse models of Huntington's disease, and ultrastructural and molecular characterisation of sub-domains within the neuronal nucleus (Dr. Michael Gilder), ultrastructural and molecular characterisation of cell death in HD transgenic mouse models (Mark Turmaine and Lee-Jay Bannister), and a detailed analysis of the ultrastructure and molecular properties of the Cajal Body, Gemmini body, PML bodies and the nucleolus (Dr. Michael Gilder, Elizabeth Slavik-Smith and Cheryl Jones).

I am expanding these investigations to encompass neurodegeneration within the CNS of transgenic mouse models of Parkinson's disease and MSA (Rushee Jolly in collaboration with Dr Michel Goedert, LMB Cambridge), investigating the role of a-synuclein in the formation of neuropathological inclusions and in a transgenic mouse model of spinal muscular atrophy (SMA) in collaboration with Dr Arthur Burghes (Columbus, Ohio).

Part I

SCIENCE FOR MAN AND MAN FOR SCIENCE

CONTEXT, ESSENTIAL CONTENTS OF, AND FOLLOW-UP TO, THE WORLD CONFERENCE ON SCIENCE HELD IN BUDAPEST IN JUNE 1999

WERNER ARBER

The World Conference on Science (WCS) was jointly organized by UNESCO and ICSU and it was held in Budapest from June 26 to July 1, 1999. Let me recall that ICSU stands for 'The International Council for Science'. On the one hand, it is a world-wide, non-governmental organization grouping, with 25 international scientific unions representing all the different disciplines of the natural sciences and mathematics. On the other, it has nearly 100 national or regional members, mostly Academies of Science with a largely interdisciplinary composition. The Pontifical Academy of Sciences belongs to this latter category of ICSU membership.

While the international scientific unions promote science at the level of specific disciplines, ICSU does so at the level of interdisciplinarity. Together with various partner organizations such as UNESCO, ICSU promotes world-wide co-operation in scientific investigations on issues of common interest by initiating and supporting special programmes. A good example is the World Climate Research Programme (WCRP). Through its multitude of co-ordinating activities, ICSU reaches a large number of scientists throughout the world. It was thus an ideal partner for UNESCO in the planning and holding of the WCS.

The aim of the World Conference on Science was to reflect on the conduct of science, its methods, its applications, and its various interfaces with human society. Therefore the WCS differed very much from normal scientific congresses with their practice of presenting recent results and discussing new ideas.

The WCS was structured into three subsequent forums. One full day was devoted to Forum I in which science and its methods were defined and the importance of international co-operation and scientific education was emphasized. This gave rise to the presentation of examples of recent advances in scientific knowledge and to an evaluation of the value of such knowledge for humanity.

Another day was devoted to Forum II in which various aspects of the interface of science with society were illuminated, such as the public perception of science, the impact of science on development, on the economy, on future generations, and on sustainability.

The WCS was attended by a total of about 2000 delegates, political leaders, scientists, and representatives of many other groups of society. Parts of the sessions were plenaries, others were split into parallel thematic meetings in which suitable time was reserved for discussions.

The three last days were made over to Forum III in which national and other delegations were allotted time to present their views on the relevance of science and its application for human society and more specifically for those nations which were represented. Although some critical voices were raised in this session with regard to some of the impacts of science, a large majority of votes were clearly in favour of a firm commitment to science and its value for the development of human society.

The generally frank and open-minded atmosphere encountered throughout the WCS might have something to do with the propensity of scientists to inter-communicate. Let me explain what I mean. Most objects of study in the natural sciences are of a global nature. Physical and chemical properties of matter are of the same nature everywhere on the planet and possibly in the universe. Similarly, major characteristics of life are shared by all organisms on all continents and in the oceans. For this reason, scientists have the habit of discussing the results of their research with each other world-wide, independently of their place of work. This communication facilitates the progress of scientific knowledge and it has the side effect of strengthening mutual trust and establishing links of personal friendship between the discussion partners. It is well known that in the practice of science, differences in opinion are not solved by fights, but by experiments and data collection, which can reveal the scientific truth. Therefore, world-wide scientific intercommunication and co-operation can have lasting effects on the establishment and stabilisation of peace, and this on a global scale.

Another interesting aspect of the conduct of science was discussed at the WCS – that of the social contract which exists between the world of science and society. Few people may be aware of this, but this social contract results from the fact that the bulk of acquired scientific knowledge serves society through helping the practical and philosophical application of available knowledge. At the WCS this long-term contract was frequently addressed, and one thus spoke of a renewal of this social contract. It is based both on mutual trust and on expectation. Society expects scientific knowledge to find applications which work to the general benefit of society, throughout the world, and scientists expect a general recognition of the cultural relevance of their work and they thus also expect the required support.

It is in this context that during a plenary session of the last day the WCS accepted by consensus two well prepared texts, one entitled 'declaration on science and the use of scientific knowledge' and the other 'science agenda – framework for action'. It is difficult to summarize these already condensed documents which deserve to be carefully read in extenso.[1] Besides explaining what science is and what its cultural contributions are, the documents represent a kind of list of rights and duties of the world of science, as well as of society in relation to science. The 'framework for action' bases its recommendations on the 'declaration' and it challenges all the partners to become seriously engaged in follow-up activities. This, of course, also concerns the Pontifical Academy of Sciences.

In the meantime both the 'declaration' and the 'framework for action' have been presented to, and adopted by, the general assembly of ICSU. More recently they have also been adopted by the general assembly of UNESCO. They have thus become binding documents. Such established engagements between society and the scientific community did not exist before the WCS.

I may mention that at the general assembly of ICSU in Cairo this fall the statements on traditional knowledge in the WCS documents were criticised, and the scientists were invited to reflect on the correct interpretation of these statements. In contrast, the major parts of the contents of the adopted documents are straightforward and free of ambiguity.

Many of the follow-up activities to be given to the WCS will concern the practical application of acquired knowledge. This may often lead to new or newly-adapted technologies in support of human welfare and commodities. Other applications may, instead, help to improve the sustainability of the environment and a more responsible use of available resources.

To finish, let me reflect on the already mentioned philosophical or

---

[1] Science International, Special Issue on the World Conference on Science, September 1999, ICSU Secretariat, Paris.

world-view dimensions of acquired scientific knowledge. I will do this on the basis of an example chosen from my personal field of research in microbial genetics. According to the Darwinian theory of evolution, biological evolution depends on genetic variations, on natural selection exerted on populations of variants, and on geographical and reproductive isolation. In most textbooks on evolution, genetic variants are said to result from accidents and errors. However, a critical reflection on available data on the molecular mechanisms of the spontaneous formation of genetic variants in bacteria indicates that this is only a minor part of the truth. Many genetic variants are, instead, brought about by the action of specific bacterial enzymes, the products of genes located in the genomes of the micro-organisms. These genes are called evolution genes as I outlined in more detail at the Plenary Session of the Pontifical Academy of Sciences of 1996.[2] The gene products referred to here are actually variation generators and they work both inefficiently and non-reproducibly. A well studied example is the transposition of mobile genetic elements which – under the influence of an enzyme called transposase – can undergo a translocation with the DNA molecules of the genome.

Another class of evolution genes controls the frequency of genetic variations by keeping this frequency low and at a tolerable level which can ensure a certain degree of genetic stability of a species. An example of this kind of gene action is found with the systems of repair of genetic alterations on DNA which may indeed be brought about by damage caused by a mutagen or also by the properties of the limited molecular stability of nucleotides.

This novel notion of the existence of specific genes serving primarily biological evolution would deserve deeper philosophical reflection. Let me just make a few relevant remarks. First, the coexistence in the same genome of genes for products responding to the needs of biological evolution and of more classical genes responding to the needs of each individual life merits particular attention. Second, the occurrence of genetic variation generators working both inefficiently and non-reproducibly may call for a reflection on the definition of genetic determination. This may also be relevant for genes other than generators of variations in the nucleotide sequences of genomes. A more realistic definition of genetic determination may have a

---

[2] W. Arber: "The Influence of Genetic and Environmental Factors on Biological Evolution", in Plenary Session, The Pontifical Academy of Sciences, on "The Origin and Early Evolution of Life" (Part I), *Commentarii*, 4, N. 3 (Vatican City, 1997), pp. 81-100.

deep impact on the public perception of the feasibility and impact of genetic manipulations. Third, while nature itself takes care of the steady evolution of life and has developed specific genes for this purpose, biological evolution is not strictly directed towards a specific goal. Rather, the direction which evolution takes depends on the life conditions encountered by the populations of organisms and on the occurrence of more or less randomly produced genetic variants in these populations. The underlying process of a steady dialogue between living beings and their environment is as a matter of fact natural selection.

It is my hope and conviction that the progress of scientific knowledge will continue to provide to all human beings on this planet both the technological and the material help to satisfy the daily needs for a life in welfare as well as a deeper understanding of the basic rules and laws of nature including its evolution. Such insights may help us in our cultural evolution to safeguard biodiversity and to ensure the sustainability of the foundations of life. These are the general goals of the social contract which was renewed between the scientific community and society at the World Conference of Science.

TECHNOLOGY: BETWEEN SCIENCE AND MAN

PAUL GERMAIN

As its title suggests, our meeting is concerned with the mutual interactions between man and science. In the present paper it is argued that between these two factors there is a new and very important entity which should also be considered and examined. 'Man', 'science' and 'technology' are very abstract words whose meaning must be made clear when they are employed. The term 'man' here refers to persons and individuals as well as to societies composed of men and women. The word 'science' (in the singular) will cover in this paper the set of disciplines which are represented within our Pontifical Academy of Sciences. The word 'technology', a singular also, will cover a great variety of different forms of technology. It is important to make a clear distinction between sciences and technologies and between technologies and techniques.

Sciences conduct research to develop, for the benefit of mankind, knowledge about the world, the earth, matter, and living beings on the one hand, and knowledge to be applied by technologies and by industrial activities on the other.

Technologies involve everything that is needed to create and produce goods, tools, things, all of which are generally very complex and which give men and women as well as societies the possibility to improve their lives and to achieve sustainable development. Moreover, they contribute to the progress of sciences because of the new kinds of apparatus and materials they provide. They reach their goals by using various results and knowledge worked out by science and techniques, but also by taking account of many constraints such as economic and financial conditions, market opportunities, production delays, prices, social acceptance, aggressive competition and so on. A technique is a skilled method by which to realise a performance or an object.

Sciences and technologies are different. Their ambitions are not the same. Sciences through research try to *discover* knew knowledge; technologies try to *innovate* and create new products. Time does not play the same role in relation to both. Competition in sciences has nothing like the decisive importance it has in technologies. To be successful, a technological activity requires the co-ordination of many actors, usually the application of many scientific results and many techniques. Very often a scientific discovery has a single author.

Obviously, scientific results play a crucial role in the success of a technology. This is why very often technology is seen as belonging to science. This seems to be the case in the principal document issued by the 'World Conference on Science' which took place in Budapest last June entitled: 'Declaration on science and of the use of scientific knowledge'. This is also probably the case in the title of the present meeting. An attempt will be made to show that one must make the distinction if one wishes to analyse in some detail the relations between the sciences and society.

1. Science and Powers

Our century has seen the emergence and the boom of technologies as a result of powerful and often multinational enterprises whose goal is specifically to make themselves always better, always more efficient, always more attractive. Thanks to these enterprises, the advance and the expansion of technologies has played the leading role in the recent evolution of our societies. Elaborate discussion is not required to be convinced of this point: military power was stimulated by the two World Wars and by the Cold War; economic power, biomedical power, communications power – all three have been very strong during the last decades; and, of course, there is also political power. These powers are very beneficial to societies because they provide them with security, sources of wealth and energy, health, the possibility to travel easily to every part of the world; they free humankind from arduous work and give the public easy access to all cultural goods. As scientific knowledge is absolutely necessary for the development of technologies, science may be rightly credited with being responsible for a large number of these important results. But, conversely, with the expansion of technologies, these powers have also brought about environmental degradation and technological disasters. They have contributed to social and even international imbalance and exclusion. The public is beginning to be anxious and afraid. In addition, science is often seen as responsible for these troubles and its image is negatively affected. That is what happens if one does not want to make a distinction between science and technology. In this situation, as the 'Declaration of Budapest' makes clear, the solution has to be found through a dialogue between the scientific community and decision-makers through democratic debate. An attempt must be made to show that to be realistic, such a statement requires a certain clarification and analysis of the respective roles of science and technology.

2. SCIENCE AND THE PROGRESS OF KNOWLEDGE

It is necessary to emphasise that the development of scientific knowledge during the last three centuries has tremendously enriched the culture of men and women; as well as the cultures of societies. Culture is what allows each person to understand himself, understand his relations with his environment and with other people, and his roots in the past generations, and to find, in this understanding, sources of fulfilment. The progress of knowledge is the result of fundamental research, research done just for the satisfaction of curiosity, which is, indeed, a fundamental character of the human spirit. *One must always stress the relevance of fundamental research for society*. Applied research is a necessary ingredient for improving technologies and these technologies are the weapons of the economic war between industrial companies and of very severe competition between arms factories. These powers try to attract the best scientists and to give financially interesting contracts to universities or to research establishments in order to stimulate the applied research that is useful for their programmes. This evolution is now so important that economists call the applied sciences developed for this improvement of technologies 'techno-sciences' and they affirm that all sciences are now becoming techno-sciences. Moreover, these companies try to patent the results of sciences which are useful to them, even sometimes results which are fundamental, and they then try to restrict the diffusion of the results. This is contrary to well established scientific tradition. This is specially true in the biomedical, in the biotechnological, and in particular in the genomic domains. Powerful firms often invest a considerable amount of money in these domains, thanks to the present policy on patents, against which scientists have not put up serious opposition. And the sums involved are far greater than is usually the case with public governmental institutions. The present economic system, which favours the creation of very powerful companies, will probably weaken fundamental research within the formal scientific sphere.

Many gifted young people hesitate today to embark on a scientific career because of the severe patenting conditions and the realities of harsh competition, rather than being attracted by the fight against the unknown in order to satisfy their own curiosity. The scientific community has to be cautious if it wants to preserve and maintain strong fundamental research. The challenge which presents itself here concerns the scientific creativity of humankind.

3. SCIENTIFIC EXPERTISE AND THE PRACTICE OF DEMOCRACY

We have seen that the technologies which are utilised and applied by biomedical or economic firms may be often very beneficial for the public, but they may also often cause difficulties and problems for nature and society. The political power may want to – and must in cases of doubt – receive advice when it has to take decisions concerning a special technology. It has to know what the causes are of its drawbacks or its dangers, what its consequences may be in the long term, whether it is better to ban it, and under what conditions it may be accepted. When scientific knowledge plays an important role in a technology, some scientists can be called in to take part in a committee which gives advice to the decision-makers. Engineers, economists, medical doctors, social scientists, and other suitable scientific experts, could also belong to this kind of committee. The questions that such a committee would have to answer are called today 'ethical questions'. Things are easy if these questions can be answered through the application of moral principles that are recognised by the great majority of people, such as human rights or human dignity. But things are more difficult for these experts in situations where the decision has long-term consequences and where ethical approaches are different. The political power may be tempted to influence the committee to give it answers which would enable it to justify its decision with reference to the recommendations of the committee. In such a case two drawbacks would exist. First, the experts would extend beyond their domain of competence. Second, they would impede the practice of democracy. What is called for is an instrument by which experts on 'spiritual, cultural, philosophical and religious values' could be added to the committee, in line with the recommendation of point 3-2 of the 'Introductory Note to the Science Agenda – Framework for Action', one of the documents adopted by the Budapest Conference. This 'Note' also argues that 'an open dialogue needs to be maintained with these values, and that it is necessary to recognise the many ethical frameworks in the civilisations around the world'. It is a pity that the principal document of the conference, the 'Declaration on Science', did not follow this recommendation. Of course such a project would be difficult to implement. But one must try. Some attempts at consensus have been made

4. SCIENCE FOR DEVELOPMENT

Obviously enough, progress in technologies, and in biotechnology in particular, may be very useful for developing countries. The documents issued by the Budapest Conference provide good analyses and good recommendations. One may simply stress here that the scientific community has to meet the needs and the expectations of these developing countries. It must be careful, and must avoid the temptations offered by big firms which are more interested in the money they may earn than in social acceptance by the local populations. Methods which are good for developed nations are not necessarily the best ones for helping poor countries. During the last three days of the Budapest meeting each delegation had the possibility of giving a short address (6 minutes) to the conference. The confidence felt by the poor countries that science could solve the difficulties of their situations was very impressive. I interpreted these contributions as an appeal to more advanced scientific communities for help. I want to hope that this appeal will meet with success. The Academies of Science provided a first response a few years ago with their creation of a new institution – 'the Inter-Academy Panel on International Issues' (IAP). It is a pity that during the meeting in Budapest and in the documents issued by the conference neither the existence of the IAP nor the 'Tokyo-IAP 2000' meeting which will take place next May were mentioned. These are two recent and new initiatives which deserve to be encouraged.

CONCLUSION

'Science for the Twenty-First Century – A New Commitment' was the title of the Budapest meeting. With its 1800 delegates from 155 countries, it was a major success. The documents which were adopted contain many useful analyses and recommendations. What has to be new for science in the twenty-first century? What should be the new commitments of scientists?

For me, Budapest 1999 was an extraordinary occasion to re-appreciate the assignments for scientific activity. I think that two principal assignments may be proposed. The first one, the traditional one, always and forever, is the progress of knowledge in relation to the unknown. It has to be protected. The international body to take care of this goal is the ICSU. The second one, which is very new, is to work in favour of the harmonious and sustainable development of all the countries of the planet by ensuring that the results and the values of sciences and techniques are integrated into the culture of each individual country and that the inequalities between and within these countries are reduced. This is a new duty for scientific activity. Academies and universities are the places where this can be worked out. At the international level, the IAP, a new institution, it is to be hoped, will take care of this new responsibility.

This implies an important mutation in the behaviour of the scientific community in the advanced countries as well as in developing countries. Thus will require new forms of solidarity and fraternity between and among all the scientists of the world.

SPINNING FLUIDS, GEOMAGNETISM AND THE EARTH'S DEEP INTERIOR

RAYMOND HIDE

Astrophysical and geophysical fluid dynamics is concerned *inter alia* with buoyancy-driven hydrodynamic (HD) and magnetohydrodynamic (MHD) flows in spinning fluids, including the Sun and other stars and the fluid regions of the Earth and other planets. Such flows are dominated dynamically by the action of gyroscopic (Coriolis) forces, and they are exemplified in the case of the Earth by HD flows within the terrestrial atmosphere and oceans and by MHD flow within the electrically-conducting liquid metallic (iron) outer core, where concomitant self-exciting dynamo action generates the main geomagnetic field (1).

The most striking features of the long-term behaviour of the geomagnetic field include reversals in polarity at highly irregular intervals, ranging in duration from *ca.* 0.25 Ma to *ca.* 30 Ma – i.e. very much shorter than the age of the Earth (*ca.* 4500 Ma) but very much longer than the time (*ca.* 0.01 Ma) taken for each reversal to occur. During the past *ca.* 400 Ma there have been two so-called 'superchron' intervals, namely the Permian Superchron from *ca.* 290 Ma to *ca.* 260 Ma ago, when a magnetic compass would have pointed south, and the Cretaceous Superchron from *ca.* 110 Ma to *ca.* 80 Ma ago, when the polarity was the same as it is now (2).

Self-exciting dynamo action involves the amplification of an infinitesimal adventitious magnetic field by the essentially nonlinear process of motional induction. Yet another generic nonlinear process in self-exciting dynamos is the re-distribution of kinetic energy within the system by Lorentz forces (3, 4). Such forces operating within a self-exciting Faraday disk homopolar dynamo loaded with a nonlinear motor can quench the large amplitude fluctuations, some highly chaotic, that would otherwise occur, thereby promoting persistent steady dynamo action (after initial transients have died away) over a very wide range of conditions, with no reversals in the direction of the dynamo current and hence of the magnetic field (3).

This recently-discovered process of nonlinear quenching could be of general theoretical interest in the investigation of nonlinear dynamical systems. If it occurs in the MHD geodynamo then it would provide a firm basis for understanding superchrons as well as other salient features (such as polarity reversal chrons and sub-chrons and polarity excursions) of the long-term behaviour of the geomagnetic field (4). According to this new hypothesis – which has implications for intensity fluctuations of the palaeomagnetic field and could also be tested in due course by analysing the kinetic energy spectrum from the output of valid numerical geodynamo models (5, 6) – those eddies in the core that are driven mainly by Lorentz forces play a crucial role in the inhibition of polarity reversals. Also crucial – and testable – is the possible role in the stimulation of reversals played by changes on geological time scales in the lateral boundary conditions prevailing at the core-mantle boundary (CMB) – where the liquid outer core meets the overlying 'solid' mantle – brought about by very slow convection and other dynamical processes affecting the lower mantle (1, 4, 7, 8). Coriolis forces due to the spin of the Earth would render the patterns of core motions, and of the magnetic fields they produce, very sensitive to modest lateral variations in the physical and chemical conditions at the CMB, which techniques of seismology, geodesy, geochemistry, etc. might in due course be capable of resolving with acceptable accuracy (7, 8).

Geodynamo studies thus facilitate the exploitation of a wide range of data in research on the structure, dynamics and evolution of the Earth's deep interior, about which much remains to be learnt (notwithstanding the great success of the theory of plate tectonics in the investigation of the *outer* layers of the Earth). As in other areas of astrophysical and geophysical fluid dynamics (e.g. dynamical meteorology and oceanography), such work is impeded by the intractability of the governing nonlinear *partial* differential equations expressing the laws of dynamics, thermodynamics and (in the case of MHD) electrodynamics – compounded in this case not only by the lack of detailed geomagnetic observations covering long periods of time but also by the technical difficulties of carrying out laboratory experiments in MHD. So thorough investigations of much simpler but physically realistic self-exciting dynamo systems governed by nonlinear *ordinary* differential continue to play an important if indirect role in studies of the Earth's deep interior.

REFERENCES

1. R. Hide, 1982, ‘On the role of rotation in the generation of magnetic fields by fluid motions’, *Philos. Trans. Roy. Soc. London*, A306, 223-243.
2. N.D. Opdyke & J.E.T. Channell, 1996, *Magnetic stratigraphy*, San Diego: Academic Press.
3. R. Hide, 1998, ‘Nonlinear quenching of current fluctuations in a self-exciting homopolar dynamo’, *Nonlinear Processes in Geophysics*, 4, 201-205.
4. R. Hide, 2000, ‘Generic nonlinear processes in self-exciting dynamos and the long-term behaviour of the main geomagnetic field, including polarity superchrons’, *Philos. Trans. Roy. Soc. London*, A358, 943-955.
5. F.H. Busse, 2000, ‘Homogenous dynamos in planetary cores and in the laboratory’, *Annua. Rev. Fluid Mech.*, 32, 383-408.
6. C.A. Jones, 2000, ‘Convection driven geodynamo models’, *Philos. Trans. Roy. Soc. London*, A358, 873-897.
7. R. Hide, 1967, ‘Motions of the Earth’s core and mantle and variations of the main geomagnetic field’, *Science*, 157, 55-56.
8. R. Hide, 1970, ‘On the Earth’s core-mantle interface’, *Quart. J. Roy. Met. Soc.*, 96, 579-590.

RECENT DEVELOPMENTS AND CULTURAL ASPECTS

YURI I. MANIN

For the purpose of this presentation, I will roughly divide mathematics into four large areas: fundamental mathematics, mathematics as the language of theoretical physics, mathematical modeling, and mathematics of modern information and communication technology (computers and networks). This subdivision reflects differences in values more than in content, but exactly for this reason it is relevant for our discussion: science for man and man for science.

1

Fundamental (or pure) mathematics deals with elaborate and subtly interwoven abstractions some of which date back to the ancient Greeks and of which some keep appearing in new issues of mathematical journals. As an example, consider Euler's famous formula $e^{\pi \iota} = -1$. In an extremely concise fashion, it relates three mathematical constants whose respective discoveries were separated by centuries and motivated by very different lines of thought.

In fact, $\pi = 3, 1415926$ is essentially a physical constant distilled to a mathematical notion in Euclidean geometry, which itself can be viewed as a physical theory: kinematics of solid bodies in a gravitational vacuum. Unlike π, the base of natural logarithms, $e = 2, 718281828$, first appeared in the great project which later became computer science, whose purpose was to facilitate time consuming numerical multiplication by replacing it with addition. Finally, the imaginary unit, $\mathrm{i} = \sqrt{-1}$ kept emerging, almost against the will of its creators, as an inscrutable but vital fragment of the formal system of algebraic notation, without which it would lack a degree of logical completeness. Euler's formula was a small wonder demonstrating the heuristic power of the recently invented calculus.

As in Euler's time, the proof of a difficult theorem, the solution of an old problem, the formulation of a striking conjecture expressing an insight into an unexplored field, are all important aspects of pure mathematics. Practitioners of pure mathematics teach at universities and pursue their research in a handful of world centers established for this purpose. They constitute a small community in each generation, whose public image, eloquently described by Hans Magnus Enzensberger, is that of insularity and detachment ([E]).

2

As the language of theoretical physics, mathematics enjoys an unusual epistemological status. The point is that the initial semantics and syntax of many mathematical notions often have nothing to do with the secondary semantics which they acquire in the context of a physical theory.

Consider an example: complex numbers and their role in quantum mechanics as "probability amplitudes". Euler's formula, mentioned above (or rather its generalization $e^{i\varphi} = \cos \varphi + i \sin \varphi$), in the context of quantum mechanics explains quantum interference and becomes the quintessence of the wave aspect of the famous wave/particle duality. The imaginary unit, and complex numbers in general, cease to be purely logical constructs and acquire a physical incarnation as quantum phases. They become as "real" as real numbers in the sense that their effects can be experimentally observed and measured. And π in Euler's formula this time does not refer to the angular measure in the Euclidean plane, which is after all only an idealized sheet of paper, but to the considerably more abstract complex plane of quantum phases.

In this way, theories developed in pure mathematics and having their intrinsic logic, are periodically reinterpreted as models of basic physical phenomena. In the last third of this century, this happened to topology and algebraic geometry with the advent of quantum strings, membranes and the project of Grand Unification in the framework of the emerging M-theory. Such unpredictable applications are often quoted in order to motivate and justify public spending on pure mathematics. In turn, physics has a profound influence on the development of mathematics. I mention only the recent successes of Feynmann's path integration in topology.

The community of physicists has grown enormously in this century, partly because of military applications, but it is not a purely modern phenomenon. It suffices to recall that Archimedes was a military engineer, and probably, if recognized and captured alive, would have had to work for Romans as Werner von Braun did for the Americans two millennia later.

3

I have set apart mathematical modeling from both pure mathematics and theoretical physics mainly because these activities differ in the minds of those who participate in them. This is discussed at some length by D. Mumford ([M]), who writes: “Models are most prominent in applied mathematics where they express the essential point at which the chaos of experiment gets converted into a well defined mathematical problem”. Galileo’s famous definition of mathematics as the language of nature was based on his experience of such conversion rather than on the fancier mathematical models that emerged later and have a more Platonic flavor.

The distinction between the models used in applied sciences and those of fundamental physics is debatable. In fact, such constructs as the Ising model show that there is no clear-cut boundary between the two. I feel nevertheless that there exists a qualitative difference between, say, the principle of superposition of quantum mechanics (which is a fundamental law) and Hooke’s law stating linear dependence of force as a function of displacement (which is only a convenient model).

More to the point, mathematical model-building includes the vast domain of models in Economics: gathering, processing and distilling statistical data into viable theoretical schemes which often enjoy explanatory and predictive force, but clearly have nothing really fundamental about them. As Mary Poovey convincingly argues in [P], this line of development, starting with Luca Pacioli’s double-entry bookkeeping, informed not only the external forms of modern economic life, but to a considerable degree also the perception of reality and even the self-perception of Western society. Poovey coined the term “modern fact” to express this notion, and thoroughly studied it in her book.

Model-building acquired a new dimension and a large new community of customers with the advent of computers. Perhaps, the most important trait of it is now the option of doing a considerable part of theoretical work by running a program (computer experiment), and/or compiling a vast database (like human genome project). Mathematics of materials (e. g. composites) or models of vision may serve as examples of scientific applications of mathematical modeling.

4

The modern industry of computers and communication networks is the technological embodiment of the abstract mathematical development dealing with the microstructure of information and information processing. The history of this development again spans two millennia, from Aristotle's classification of syllogisms to Turing's machine.

Somewhat paradoxically, with the advent of personal computers and Internet this has become the most visible and most widely used mathematical product. Moreover, user-friendly technological solutions allow one to become a customer of such a system without being burdened by knowledge of mathematics, much in the same way as we drive cars without having to understand thermodynamics and the kinetics of internal combustion.

As I have tried to show, mathematics supported many processes which were vital for the development of modern society and which determined its present state. This role of mathematics raises various issues which I will present in the same order in which I have discussed the sociology of the mathematical community.

5

Pure mathematics traditionally was regarded as a part of high culture, on par with, say, philosophy and music. Edna St. Vincent Millay's line, “Euclid alone has looked on Beauty bare” only a century ago was a poetical expression of commonplace wisdom. This view is now challenged by several cultural shifts.

Academia, with its traditional network of independent universities, libraries, publishing houses and its peer review system, is evolving in the direction of becoming a specialized training and research ground, a part of the service industry subject to market economy laws (especially in the USA), or responsible and directly accountable to government agencies. Consumerism generally lowers cultural standards and tends to dilute or even completely exclude from the curriculum courses requiring hard work and not leading to the immediate and materially rewarding career openings. Mathematics especially suffers from these tendencies.

Applications of mathematics to industry and biology are challenged by the New Age sensibilities. Environmentalists blame science and technology for the destructive uses we made of them, thus further diminishing their cultural appeal.

On the opposite end of the spectrum of intellectual life, deconstructionist and postmodern trends of discourse put in doubt the very notion of scientific truth, trying to replace it by highly arbitrary intellectual constructions, based upon Freudian fantasies and ambiguities of natural language. Moreover, the grand culture of European origin or cultivation is diminished in stature by such pejorative connotations as cultural imperialism and Eurocentrism.

H. Bertens in [Be] argues that postmodernism is essentially positive and compatible with left-liberal political trends, whose essence is “self-reflexivity that leads to the unmasking of prejudices and exclusionist strategies”. In particular, in his words, “culture at large becomes aware of its hierarchical structure – with white males at the top of every heap – and begins a long march, far from over, on the road to redressing all sorts of historical wrongs”.

These noble intentions notwithstanding, implications of such a mindset for science, its values and its goals, are far from being positive. In fact, they lead to a wild politization of any discourse involving science. In extreme cases they involve misrepresentations of its content and meaning (as was demonstrated by Socal and Bricmont in their analysis of some canonical postmodern texts), and even complete negation of the central notion of science, that of objective truth. As a frustrated Galileo asked in 1605, “What has philosophy got to do with measuring anything?” Four centuries after, we still seem to be unsure about the answer.

This school of thought replaces serious thinking by soul-searching and collective psychotherapy thus effectively preventing our community from seeking responsible answers to the problems of modernity.

Computers and the Internet, helping to solve some of these problems and permitting unprecedented freedom of communication, pave the road to changes, the full scope of which we cannot as yet foresee. As an example, one can cite their role in financial markets which arguably have brought us closer to the dangers of global economic instability. Other concerns are related to the whole structure of information storage and processing in modern society, which is becoming increasingly dependent on quickly mutating and obsolescent hardware and software.

Victor Hugo remarked in “Notre Dame de Paris” that books killed cathedrals (meaning that Enlightenment culture replaced medieval Christian culture). It looks now as if computers are killing books.

Let me quote I. Butterworth: “...the American Association of Computing Machinery, the main US learned society in the computing area, with 18 journals totaling 30000 pages per year, plans to stop completely its printed versions by the year 2000. It is common to hear in such societies statements like ‘We want to destroy print’”.

There are qualitative differences between libraries and electronic archives. On the positive side, new technology provides the speedy and universal storing of, and access to, information, including papers, books and databases; visual and sound materials; flexible electronic linking; and much more. On the negative side, the life span of the supporting hardware and software is alarmingly short: “...the hardware on which digital information is to be recorded and accessed has a typical life of 10 years” and, moreover, “to a first approximation, no one can use a piece of software written 10 years ago. [...] Maintaining an archive therefore requires expensive human involvement to ensure that, by continual re-copying and by updating of protocols, it can still be accessed. [...] Commercial publishers may be willing and even anxious to maintain archives as long as they have commercial values as databases, but would presumably then allow them to die. If research and scholarship are not to become ephemera, active archives will probably have to be maintained by a combination of learned societies and national legal deposit copyright libraries – but the operation will not be cheap” ([Bu]).

Finally, we are becoming more acutely aware of the dangerous effects of the “stupidity amplification” phenomenon, the Y2K problem being only one of its most outrageous instances.

The fate of mathematics depends on the fate of society. Mathematics was traditionally considered to be the finest expression of rationalism. We must demonstrate again and again that being rational also means being moral.

REFERENCES

[Be] H. Bertens, ‘Postmodernism: the Enlightenment Continued’, *European Review*, 6:1 (1998), 35-43.

[Bu] I. Butterworth, The Impact of Electronic Publishing on the Academic Community, *European Review*, 6:1 (1998), 97-102.

[E] H. M. Enzensberger, *Zugbrücke au.......er Betrieb/Drawbridge Up* (A. K. Peters, Natick Ma, 1999).

[M] D. Mumford. *Trends in the Profession of Mathematics* (DMV Mitteilungen, h. 2, 1998), 25-29.

[P] M. Poovey. *A History of the Modern fact. Problems of Knowledge in the Sciences of Wealth and Society* (The University of Chicago Press, 1998).

SCIENCE AS UTOPIA

JUERGEN MITTELSTRASS

Utopias are emigrated wishes; science is a way to recover them. What do we mean when we say that science has a utopian character and is a utopia? Is not science real? Is not science an essential part of our academic life and an essential part of the modern world? In this paper I shall propose four brief theses to describe the utopian element in science and its peculiar infinity.

1. *Uncompleted Science*

Science is never perfect; it is always something that is unfinished – not in the sense of a defect, but as something that belongs to the essence of science, to its peculiar infinite character. If science were something which could be completed, that is to say, if at some point everything that can be explained with scientific methods were to be explained; if at some point all questions that can be posed scientifically were to be answered; and if at some point everything that can be mastered with scientific methods were mastered, then science itself would be a mere means, an artefact, not a process – at least not in the sense that science constitutes precisely the future potential of a technical and rational culture such as ours. It would be as if one took rationality or reason to be something which could be completed, to be something that one could at some point have at one's disposal as a perfected good. But rationality and reason are, in opposite fashion, never completely fulfilled. They are demands upon thought and action that must be constantly aroused, at least in the wake of the European Enlightenment. They are demands whose sense lies not in their complete realisation but rather in their 'infinite' contribution to orientation.

This is the case, too, with science. In science we find expressed the 'infinite' will of man to comprehend his world – and himself – and even more to make it his own work. That this, too, in turn, is an infinite task lies not in the fact that this task itself is utopian – we already live in a world which is to an ever increasing extent the product of scientific and technical understanding – but rather in the fact that there are no scientifically final answers to the question of how the world of man, insofar as it is (also) his product, should look in the end, and how mankind, even with scientific means, should understand itself. Furthermore, science is extremely inventive, not only in its results but also in its questions, and it is inexhaustible, just as understanding and reason are inexhaustible. 'Science as Utopia' is an expression of this 'infinity' of science or of a scientific culture, and it is the expression of the insight that science – again, like understanding and reason – always has its essence ahead of it, that is to say it always lives in the awareness that it is not what it is supposed to be, namely – in the words of the German Idealist Fichte – absolute knowledge. Such knowledge is indeed a pure utopia, but a useful one: it keeps the process of science and the process of knowledge in general in motion.

2. *Transdisciplinarity*

The scientific spirit is in motion – not only along the usual paths of research but also with regard to its own disciplines. Disciplinary orderings are increasingly replaced by transdisciplinary orientations. Transdisciplinarity means that research is to a great extent in motion out of its disciplinary limits, that it defines its problems independently of disciplines and solves them by passing beyond these boundaries. The institutional expressions of transdisciplinary orientations – which are effective wherever a strictly disciplinary definition of problem situations and problem solutions no longer fits – are the new scientific centres that are being founded or have already been launched, such as the Harvard Center for Imaging and Mesoscale Structures or the Stanford Bio-X Center. These centres are no longer organised along the traditional lines of physics, chemistry and biology institutes or faculties but rather from a problem oriented perspective, which in this case follows the actual development of science. Transdisciplinarity proves to be a promising new research principle. Where it is in place, the old institutional structures begin to look pale. Research is looking for a new order.

The development of science in a transdisciplinary direction may even reawaken the notion of a *unity of science*, which during the development of modernity replaced the older notion of the unity of nature. But this notion of a unity of nature seems also to have gained ground once again (in science and philosophy), at first as the conception of a unified physical theory – if there is only one nature, then all natural laws must also be part of a unified theory of nature – then in the form of increasingly transdisciplinarily-oriented scientific research. If nature does not distinguish between physics, chemistry, and biology, why should the sciences that study nature do so in a rigid, disciplinary manner?

The unity of science and the unity of nature may well be philosophical dreams, but their basis – ever more strongly integrative, indeed, transdisciplinary research – is real. Some examples are: (1) nanotechnology, in which physicists, chemists and biologists work hand in hand in the production and investigation of nanostructures; and (2) foundational questions of quantum mechanics, which are worked on in cooperation by physicists with very differing backgrounds, especially mathematical physicists and researchers in the field of theoretical and experimental quantum optics, and by information scientists and philosophers; but also (3) monistic and dualistic explanatory conceptions within the framework of solving the so-called mind-body problem, in which originally purely philosophical approaches are connected with research in neurophysiology and neuropsychology into the empirical connections and mutual dependencies of physical and psychical states and processes. Transdisciplinarity is constantly reinventing science – and in this way it remains close to science's 'infinite', and thus also always utopian, essence.

3. *The Limits of Science*

There is scarcely a place where the unfinished, 'infinite' or utopian character of knowledge and of science is made more clear than in the question of the *limits of knowledge and science*. It is all the same whether *practical* limits are meant, that is, limits presented by our comprehension and the means it has at its disposal; *moral* limits, that is, limits that place knowledge acquisition and science under ethical categories; or *theoretical* limits, that is, limits that cannot be overcome – independently of practical and moral limits. Here we are concerned with the question of a *de facto* finitude, which would connect the utopian with knowledge and science, this time in a negative sense.

The philosophy of science discusses this question, usually with reference to the natural sciences, in the form of two theses. (1) The thesis of the complete or asymptotic *exhaustion of nature*. According to this thesis, the history of scientific discovery is either absolutely finite or at some point goes over into an asymptotic approximation to what can be known. The place of innovations would be taken by filling-out and mopping-up operations, the calculation of additional decimal points, and the classification of additional cases, which tell us nothing that is essentially new. (2) The thesis of the complete or asymptotic *exhaustion of information capacities*. According to this thesis, the scientific information possibilities are either again absolutely finite or at some point go over into an asymptotic approximation to absolute limits of information. Here, too, filling-out and mopping-up operations would take the place of innovations. Science would have exhausted its own research and articulation possibilities; between it and a possibly unexhausted nature there would rise an insurmountable information barrier. The crucial question – whether scientific progress still has a future – would only be apparently paradoxical. However, within the boundaries of the two theses presented, this question is unanswerable, and this, too, speaks in favour of the infinite and the utopian in the affairs of science.

One reason for this is that *questions*, and in particular scientific questions, know no bounds – what would be the sense of saying that all questions are answered? (At best, saints could talk like this). And the *goals*, in this case goals pursued by scientific knowledge, are similar. If research is not determined only by the respective state of research already reached (for instance with regard to answering scientific questions), but also by the (internal and external) goals tied to it, then the notion of an end to scientific progress would not only include the assertion that we know everything (that we can know), but also the assertion that we know all goals (that we can have). The number of these goals, however, is unlimited even if we accept the limits ascribed to the scientific permeation of the world and of mankind. But this means that in order to be able to answer the question – whether scientific progress has a future – we would in a certain way already have to know what we do not know now, that which only scientific progress or its failure could show. In this sense there are no limits to science.

4. *The Phoenix*

What I have said about transdisciplinarity applies to scientific thinking in general: scientific thinking, so to speak, constantly invents itself anew, realises itself in its constructions and destroys itself with its constructions. The phoenix is the symbol of science just as the owl is the symbol of philosophy. Science creates itself just as philosophy constantly looks at itself and what it has seen. Science lives from the mortality of knowledge, philosophy from the immortality – or better, from the infinity – of reflection, which also constantly meets itself, while science forgets and discovers. Only the concept of construction holds the two together. For philosophical reflection, too, – as long as it does not just reproduce itself hermeneutically in a state of infertility – constructs, designs new worlds and fills them again with its grown-old experiences.

Returning once again to the beginning: if science knew everything that it could know, it would in a certain sense be perfect in its limitation and finitude, that is to say, everything that could be explained according to its own questions would be explained; everything predictable according to its cognitive base would be explicated; everything cognitively demanded according to its own epistemic intentions would be available as an instrument; and what is given with the above mentioned perfections would leave no room for other things to be explained. But this notion suffers from the above mentioned circumstances connected to the infinitude of our questions and our goals. Scientific progress is thus limited neither by an attainable perfection of knowledge nor by absolute theoretical limits of knowledge – however, there are practical limits. For the limits of science are either *limits of error* (the scientific intellect is stymied by its own insufficiencies) or *economic limits* (scientific progress becomes unaffordable) or *moral limits* that are always given whenever scientific progress turns against mankind itself. Whatever the case, every measure of science that puts limits to its progress is a practical measure and thus a self-given measure. And this, too, means that science is always essentially something unfinished: uncompleted limits and uncompleted limitlessness – the concrete utopia of science.

FROM MODERN RESEARCH IN ASTROPHYSICS TO THE NEXT MILLENNIUM FOR MANKIND

GEORGE V. COYNE

Introduction

The organizers of this meeting have requested that "the papers should take the form of sets of suggestions rather than academic lectures". I will, therefore, make two suggestions and support them by a brief review of several areas of research in modern astronomy. Among those areas I will emphasize the search for extra-solar planets and planetary systems.

Suggestions

I would like to suggest that all of our planning for the Plenary Session and other activities of the first year of the new millennium take into account the following two conclusions which can be drawn from the most recent research in astrophysics: (1) there is increasing evidence that we may not be alone in the universe; (2) public opinion to the contrary, our scientific knowledge of the universe is very limited.

We must be very careful in our formulation of the first issue. The question to be addressed is not whether there is extraterrestrial intelligence, since there is no scientific data whereby to even approach an answer. The question is rather: Are there the physical conditions for Earthlike life elsewhere in the universe? In other words, is there any evidence that there are planets like the Earth about stars like the Sun with the macrophysical conditions for life?

As to the matter of our ignorance as regards our scientific understanding of the universe, a brief review will suffice to indicate the limited frontiers of our knowledge. The most significant fields of modern astronomical research extend over a wide range of topics including the physics of the early universe to the search for extra-solar planetary systems. We shall do that review of selected topics now and subsequently speak in more detail of the search for extra-solar planets.

Selected Topics in Astrophysics. Frontiers of Ignorance

By combining elementary particle physics with quantum cosmological models we have a solid understanding of the very early universe, although not its origins. Less well known are the epochs of the formation of structure in the universe: galaxies and clusters of galaxies. Despite intense efforts to determine the ultimate fate of the universe, we do not yet know whether the mass of the universe exceeds the critical mass to close it. More than a decade of attempts to identify the dark matter in the universe have left us still in doubt, although the observational evidence for its existence is overwhelming. Let us review these topics in more detail.

The deep field observations with the Hubble Space Telescope challenge all theories accepted to date for the development of structure. A principal difficulty is that the observations indicate that structure developed much earlier than can be accounted for in any of the expanding universe cosmologies. The detection of non-homogeneity challenges inflationary models. It is not yet known with certainty as to whether galaxies formed from a single massive proto-galactic cloud or whether they formed from mergers of smaller regions where star formation had already begun. This uncertainty is fundamental and is shown graphically in the schematic diagram of the evolution of the universe in Fig. 1. The formation of galaxies at one billion years and of the first stars at five billion years is essentially unknown!

The great success of Big Bang cosmologies during this century may conceal some of the principal problems still remaining. Chief among these is the determination of the distance scale and, therefore, the time scale for the expanding universe. The Hubble law relates the velocity of expansion of the universe, determined by measuring the red-shifts of galaxies and clusters of galaxies, with distance. This is shown in Fig. 2. It is important at this point to note an observational problem associated with the Hubble law. The observational error associated with measuring a red-shift does not depend on distance, whereas the error in measuring distance increases enormously with increasing distance. For large distances we must make many assumptions about the uniformly mean brightness of certain kinds of intrinsically bright objects, for instance, supernovae or globular clusters, and we must apply assumed corrections for the aging of such objects.

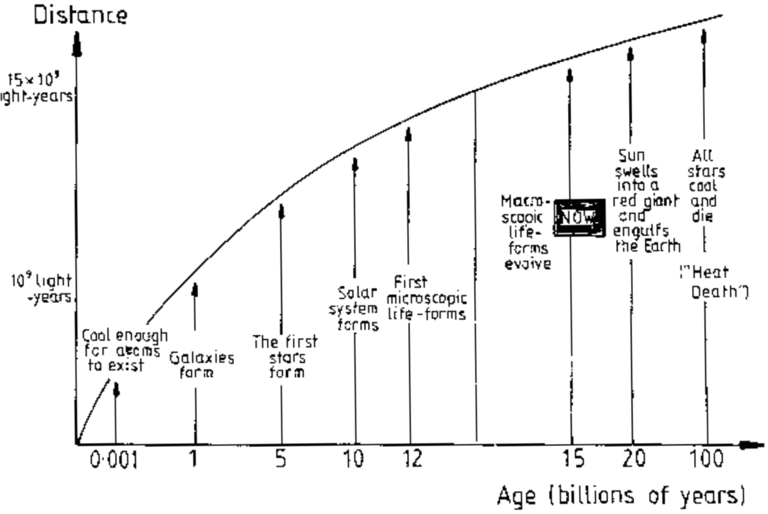


Fig. 1 – A schematic of the expanding universe. As the universe gets older (abscissa) the distances between objects increase (ordinate). The epochs at which various principal events occurred are indicated by arrows. Although shown here, we are not certain about the epochs at which galaxies and the first stars formed.

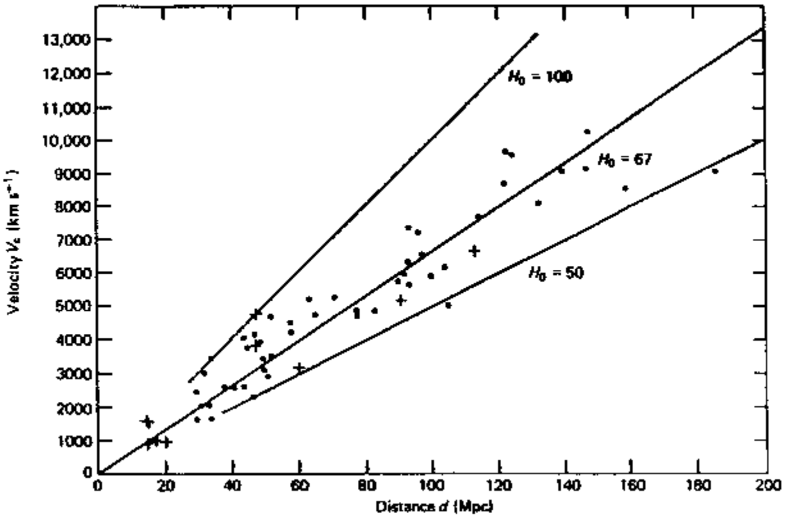


Fig. 2 – The Hubble law shows the velocity at which the universe is expanding at various distances (1 MPC [megaparsec] = 3.3 million light years). The Hubble constant, H, is the slope of the relationship and is inversely proportional to the age of the universe. The three lines show the extreme values and the mean value to the scattered observations.

The distance limit for the so-called primary methods of measuring cosmological distances is about thirty million (3×10^7) light years, only two thousandths of the way back to the Big Bang. For larger distances the observational errors result in an uncertainty in the slope of the Hubble law (the Hubble constant), which is roughly inversely proportional (a specific cosmological model with a given deceleration parameter must be assumed) to the age of the universe. Recent observations with Hubble Space Telescope (HST), for instance, indicate a change in the distance scale which would essentially decrease the currently estimated age of the universe by a factor of two. In that case we would have some globular clusters of stars, whose ages are known by methods completely independent of the Hubble law, with ages about twice that of the universe itself. A problem, indeed! It is of some interest to note the history of the determinations of the Hubble constant. The age of the universe has roughly changed by a factor of five in the course of fifty years!

Two increasingly difficult problems are the quantity and nature of dark matter in the universe and whether the universe is open or closed. The two problems are related. From the observed rotation curves of spiral galaxies and from the gravitational binding of rich clusters of galaxies, it has become increasingly clear that about ninety percent of the gravitating matter in the universe does not radiate What is the nature of this dark matter which is so predominant?

We know that the universe is tantalizingly close to being either open or closed. There are two approaches to try to resolve which is the case. If we could measure the curvature of the Hubble law at large distances, then with certain reasonable theoretical assumptions, we could resolve whether the universe was open or closed. This is shown schematically in Fig. 3. As we look at large distances, we are looking back in time and we can compare the observed expansion rate then to that in more recent times. We can, therefore, in principle, determine the rate of deceleration of the expanding universe and whether such a rate is sufficient to close the universe. The observational problem is precisely the one which we have discussed previously and is shown by the scatter of the points in Fig. 3. Errors in the measurement of large distances will not allow us to determine accurately enough which of the Hubble curves (A, B, C or D) is the true one.

Another approach to determine the closure or not of the universe is to measure the mean density of the universe. If the mean density is greater than a critical value, estimated to be about five H atoms per cubic meter, then the universe is closed. This is a very sound approach, based on the

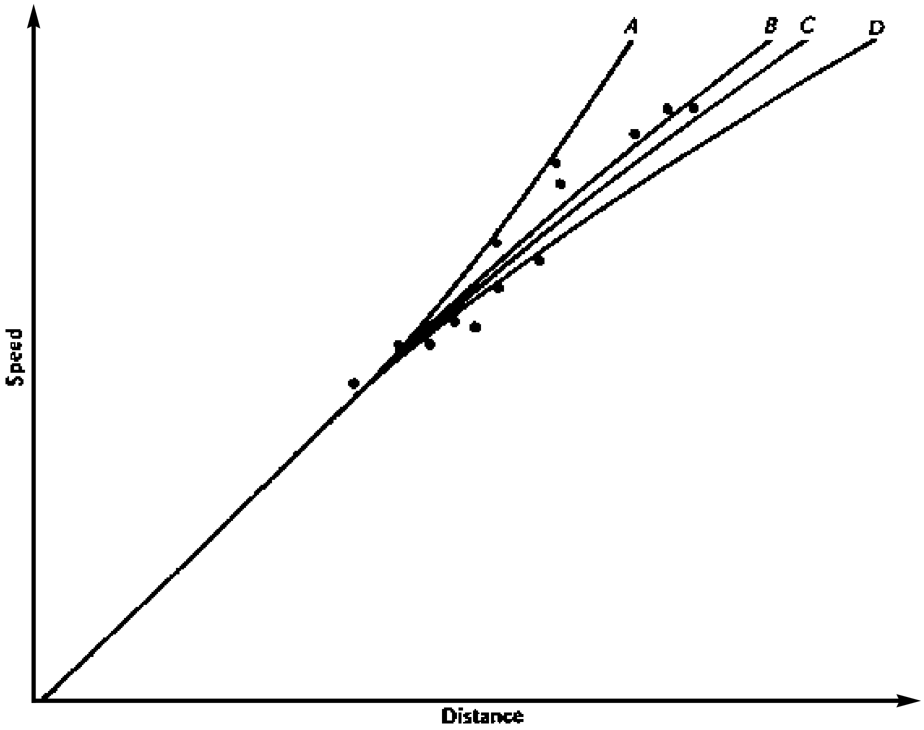


Fig. 3 – Because of the uncertainty of the Hubble law at large distances, due to increasing errors in the distance measurements, it is difficult to decide which of the curves, A, B, C or D describes the real universe. Thus, we do not know whether the universe is open or closed.

simple working of gravity, but how are we to measure this mean density when it is estimated that ninety percent of the matter in the universe is not radiating? We are left with the uncertainty as to whether the universe will end at all and, if so, whether with a crunch or a whimper.

Extrasolar Planets. Theory and Observations

The best model we have for the formation of planets about solar-like stars is shown in Fig. 4. A large interstellar cloud, typically containing 10^3 masses of the sun, fragments due to an interplay of kinetic, gravitational and magnetic energy. Each fragment that is sufficiently compact and sta-

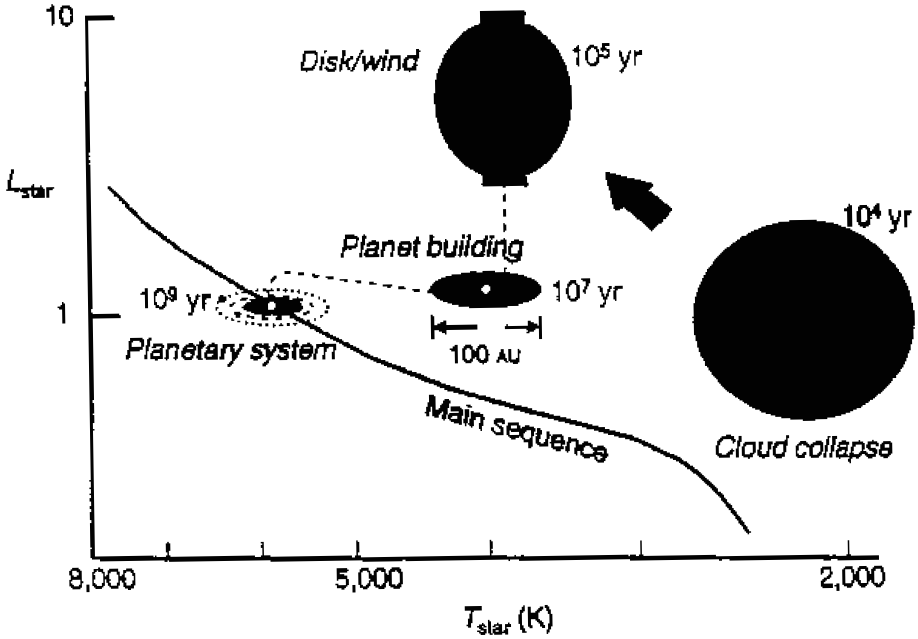


Fig. 4 – The scenario for the birth of stars and planets. See text for explanation.

ble begins to collapse by self-gravity and, like any normal gas, as it collapses it heats up. If it is sufficiently massive (more than about 0.1 the mass of the sun), it will raise the temperature in its interior sufficiently high, so that thermonuclear burning begins. At this point a star is born. (This is called a pre-main sequence star, since it is not yet completely stable.) For a star with a mass equal to that of the sun this process takes about 10^7 years. For more massive stars it is shorter, for less massive stars longer. The sun will keeping shining as it does today for about 10^{10} years and then it will explode and become a white dwarf. Note, therefore, that a star like the sun is born relatively (relating “gestation” to “lifetime”) fast, some ten times faster than the birth of a human being! In the course of the cloud collapse there are stages which are important for the formation of a planetary system. As the star collapses, in order to conserve angular momentum, it rotates and this rotation cause a continuous flattening of the cloud until at the end of 10^7 years a disk has formed. There is also an intermediate stage after about 10^5 years at which a wind of high energy particles sweeps through the cloud and carries away much of the material left over from the collapse.

So, we have a solar-like star with a rotating disk of hydrogen gas and dust about it. How do planets form within this disk? As the disk continues to rotate the material in it begins to separate out into rings according to the mass distribution. Within each ring conglomerates begin to form due to elastic collisions, gravity and electrostatic binding. Eventually larger conglomerates, called planetesimals, of the order of 100 kms in extent are formed and then from these the planets are formed. During these processes the lighter elements are preferentially driven to the outer parts of the disk due to temperature of the parent star and the stellar wind. This explains why the outer planets in the solar system are more gaseous than the inner planets. Thus, for a star like the sun we have after about 10^9 years a stable star with a planetary system about it.

Patient and painstaking research over the past decade has led to the discovery of more than fifty planets about other stars. These planets have been discovered by analyzing the systematic oscillations in the motion of the parent star or, in rare cases, by the direct measurement of the displacement of the star on the sky. Examples of such measurements are shown in Fig. 5. Only massive planets near to their parent star can be discovered in this way. Jupiter, for instance, could not be detected in this way from the nearest star to the Sun. So, the method is very limited. In no case, do we have an Earth-like planet in a habitable zone. A sample of planets discovered thus far is shown in Fig. 6.

At times there is an ambiguity as to whether the object discovered is a “brown dwarf” or a true planet. If a collapsing cloud has less than about 0.1 solar masses it cannot raise the internal temperature high enough to start a thermonuclear furnace; so, no star is formed. The object still shines but not by thermonuclear energy. It has short-lived residual gravitational energy and is called a “brown dwarf”. The division between “brown dwarfs” and planets is ambiguous and it is difficult to separate out these objects. Planets form by the accretion of planetesimals; “brown stars” form like stars do by the collapse of a cloud fragment. So, the formation processes are very different; but the resultant object may lie on the observational borderline.

An increasingly fruitful area of research is the detection of proto-planetary disks about young stars. Very high resolution imaging is required and thus far only Hubble Space Telescope has succeeded. In some of the disks detected we have indications that the formation of planets has

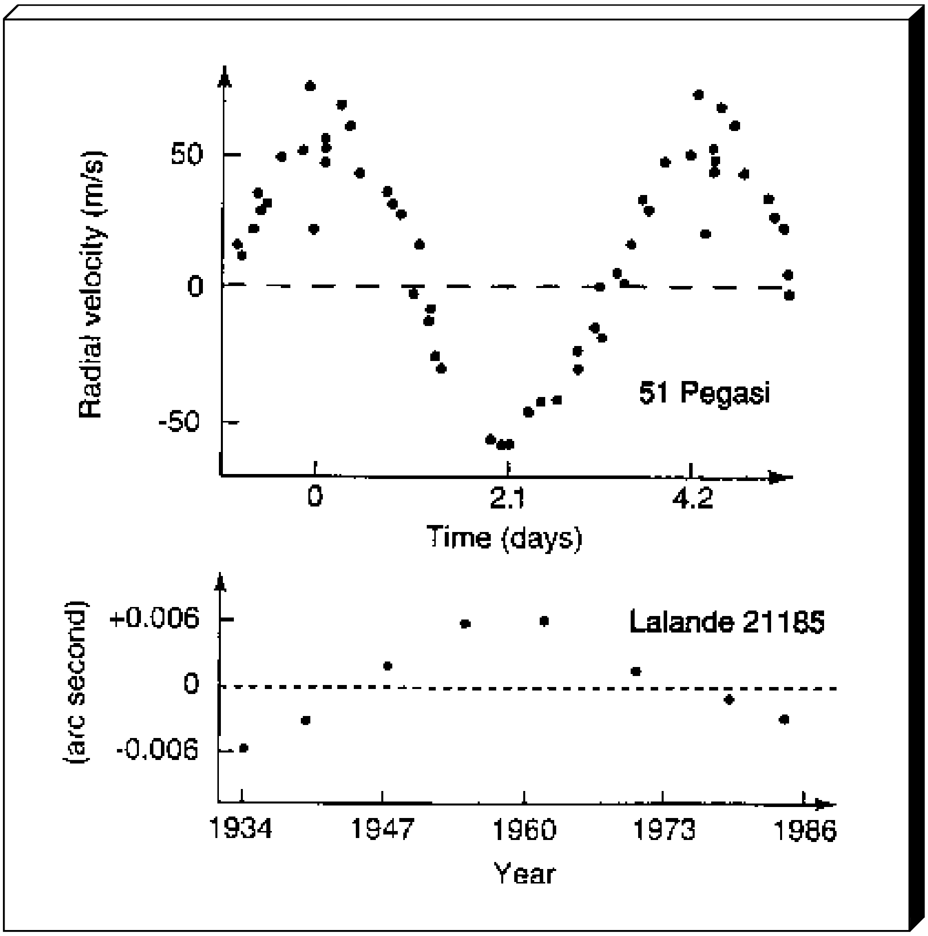


Fig. 5 – The oscillations in the line of sight motion of the star 51 Pegasi reveal the presence of a planetary object in orbit about the star. The periodic variation in the position of the star Lalande 21185 likewise reveals the presence of a planet.

already begun. There is a well-founded hope that in the near future we will not only discover many planets but also planets in formation. This, of course, will provide an immense leap forward in our search for the physical conditions for extraterrestrial life.

The conclusions to be drawn from the observations to date are: (1) the discovery of extra-solar planets by studying the motion of the parent star is

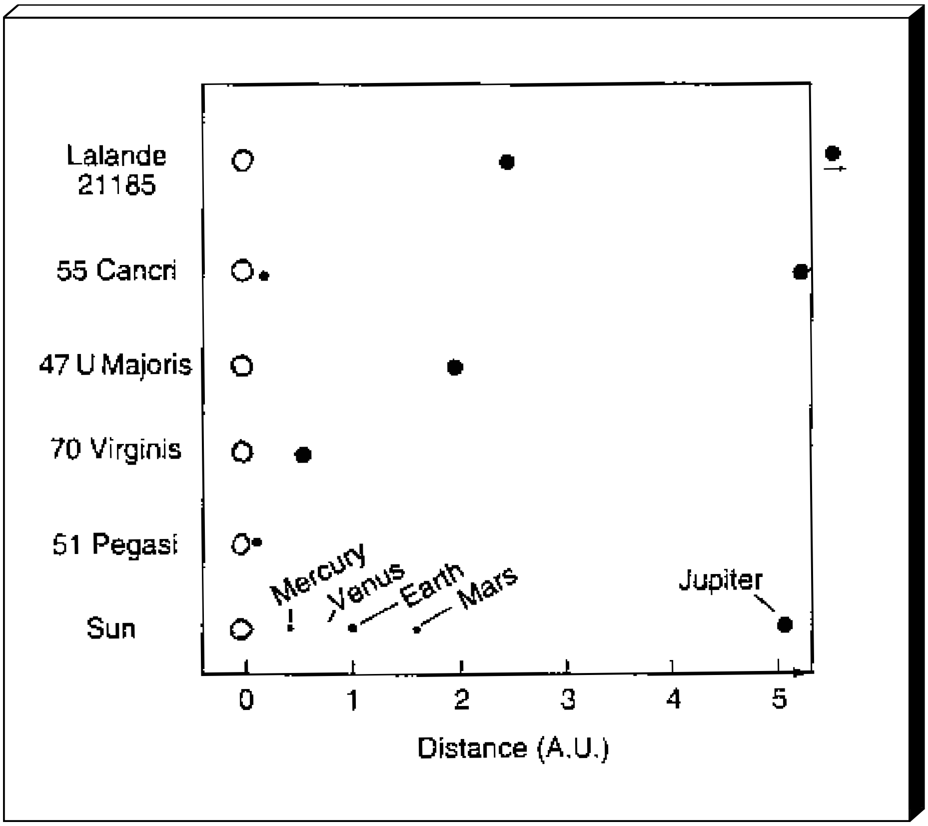


Fig. 6 – A sampling of planets (filled circles) recently discovered about nearby stars (open circles)

promising, but the results thus far are few; (2) some of the objects discovered thus far may actually be “brown dwarfs”; (3) no Earth-like planets in a habitable zone have been discovered.

Other techniques, such as high-resolution imaging in space and from the Earth, spectroscopic detection of extra-solar planetary atmospheres etc., are being developed. Ambitious programs are being developed to search by spectroscopy for biotic or pre-biotic conditions in extra-solar planets. Within the next decade we will undoubtedly discover hundreds of candidates as extra-solar planets. In 2004 the NASA will launch the Full-sky Astrometric Mapping Explorer (FAME), a space telescope designed to obtain highly precise position and brightness measurements of 40 million stars. This rich database will allow astronomers to determine with unprecedented accuracy the distance to all stars on this side of the Milky Way galaxy and to detect large planets and planetary systems around stars within 1,000 light years of the Sun. While that will be a sampling of only one percent of the distance across the Galaxy, it will increase by a factor of at least 100 the distances thus far sampled. It appears, therefore, from an observational point of view, that we will soon know whether the existence of planetary systems is a common phenomenon.

Questions for the Future

The convergence of many fields of research in modern astrophysics allows us to pose some scientific questions about the origins and evolution of the universe as a matrix from which life has evolved. We are intimately related to the energy and the matter in the universe of which we are a part. We are constantly exchanging atoms with the total reservoir of atoms in the universe. Each year 98% of the atoms in our bodies are renewed. Each time we breath we take in billions and billions of atoms recycled by the rest of breathing organisms during the past few weeks. Nothing in my genes was present a year ago. It is all new, regenerated from the available energy and matter in the universe. My skin is renewed each month and my liver each six weeks. In brief, human beings are among the most recycled beings in the universe. Life has made a relatively late appearance considering the total age of the universe (see Fig. 1) and there are three intriguing questions which it poses in terms of the evolution of the universe itself: (1) in the evolving physical universe was it inevitable that life come to be; was it by chance; can it be understood; (2) is life unique to our planet; (3) is life at the level of intelligence and self-reflection an important factor in the future evolution of the universe?

THE ROLE OF TROPICAL ATMOSPHERIC CHEMISTRY IN GLOBAL CHANGE RESEARCH: THE NEED FOR RESEARCH IN THE TROPICS AND SUBTROPICS

PAUL CRUTZEN

The main permanent components of the atmosphere N_2, O_2 and Ar together make up more than 99.9 volume % of the atmosphere. Nevertheless, the Earth's climate and the chemistry of the atmosphere are mainly determined by the remaining minor constituents, which because of their relatively low abundance are significantly affected by human activities, in particular by fossil fuel and biomass burning, chemical manufacturing, agriculture and land use changes. Most abundant among these gases is carbon dioxide, which plays essential roles as the carbon feedstock for the photosynthesis of plant matter and for the Earth's climate. CO_2, however, does not play any significant role in the chemistry of the atmosphere. Among the chemically active gases, methane (CH_4) is most abundant with a volume-mixing ratio of about 1.7 ppmv, compared to a pre-industrial value of only about 0.7 ppmv. Methane plays important roles in the photochemistry of both the troposphere and the stratosphere. The next most abundant gas of chemical importance is nitrous oxide (N_2O). Chemically almost inert in the troposphere, N_2O is removed from the atmosphere by photochemical destruction in the stratosphere. A fraction of the nitrous oxide is thereby oxidized to nitric oxide (NO), which, together with NO_2, acts as a catalyst in an ozone-destroying cycle of reactions. In the natural stratosphere, the production of ozone (O_3) by the photodissociation of O2 is largely balanced by its catalytic destruction by NO_x (= NO + NO_2). Because the abundance of N_2O is increasing by 0.2 – 0.3%/year, partially due to the increased production of N_2O in soils as a consequence of the rapidly growing application of N-fertilizer, there is an anthropogenic effect on stratospheric ozone, although at a relatively slow rate. The most important anthropogenic impact on stratospheric ozone is due to the emissions of a series of entirely manmade chlorine – (and bromine) containing compounds, in particular $CFCl_3$, CF_2Cl_2, and CCl_4. As with N_2O, these gases are only removed from the atmosphere by photodissociation in the stratosphere, thereby producing Cl and ClO radicals, which, even more efficiently than NO_x, diminish ozone, by catalytic reactions. Most surprisingly, the strongest depletions in stratospheric ozone have been found to occur over Antarctica during the springtime months of September and October. Exactly in the height region (14-21 km) where naturally, and until about 2 decades ago, a maximum in O_3 concentrations was found, O_3 has now totally vanished, resulting in major depletions in the total ozone abundance in the atmosphere and major increases in the fluxes of biologically damaging ultraviolet, so-called UV-B, radiation at the Earth surface.

The functions of ozone in the atmosphere are manifold. It acts as a filter against solar ultraviolet radiation, thereby protecting the biosphere from a large fraction of the biologically active radiation of wavelengths less than about 310 nm. About 90% of all ozone is located in the stratosphere and 10% in the troposphere. Both are substantially affected by human activities. Contrary to what has happened in the stratosphere, ozone concentrations in the troposphere have increased, as is clearly noticed during photochemical smog episodes, but also more generally in regions that are affected by anthropogenic emissions of methane and other hydrocarbon, carbon monoxide (CO) and nitric oxide (NO), such as the mid-latitude zone of the northern hemisphere and also the continental tropics and subtropics as a consequence of biomass burning during the dry season. Ozone is deleterious to the biosphere, affecting human health and plant growth, especially agricultural productivity.

The role of ozone in the troposphere is, however, not only negative. In fact, it fulfils a very important function in the removal of almost all gases that are emitted into the atmosphere by nature and human activities. The latter occurs mainly via reactions with hydroxyl (OH) radicals which are largely formed by the absorption of solar UV-B radiation by ozone, leading to the production of electronically excited O atoms which have enough energy to react with water vapour to produce hydroxyl radicals. Despite very low tropospheric concentrations, globally averaging about 4×10^{-14} by volume, it is hydroxyl, and not abundant molecular oxygen (O_2), which is responsible for cleaning the atmosphere. Because of maximum abundance of UV-B radiation and water vapour, the concentrations of hydroxyl radicals are largest in the tropics and subtropics. A quantitative understanding of the chemistry of the atmosphere requires, therefore, good knowledge of the chemistry of the tropics and subtropics.

Specifically in the tropics and subtropics there exist major gaps in knowledge and observations of many key species in tropospheric chemistry, in the first place of ozone, but also of those species which determine the oxidizing efficiency (that is OH concentrations) of the atmosphere, such as CO, hydrocarbons and NO_x. The continental tropics and subtropics are already substantially affected by mostly human-caused biomass burning. In future, agricultural and industrial activities will particularly grow in these regions on the globe. The study of the influence of these on atmospheric chemistry (e. g. ozone and hydroxyl concentrations) and climate is an important task for the atmospheric chemistry community. This requires much enhanced research activities in the tropical world which should also involve researchers from the developing world.

The present state of quantitative knowledge about particulate matter in the troposphere is even in worse shape than that of the gas phase. The role of aerosol is manifold:

1. Particulate matter can influence the chemistry of the atmosphere by providing surfaces and liquid media for chemical reactions, which often can not take place in the gas phase.
2. By the scattering and absorption of solar radiation, particulate matter plays a substantial role in the radiative properties of the atmosphere and, therefore, in the Earth's climate.
3. This influence is emphasized by the fact that atmospheric particles can serve as condensation and ice-forming nuclei. Recent studies have indicated the possibility that climate warming due to increasing levels of greenhouse gases has been substantially counteracted by the backscattering to space of solar radiation, both directly from the aerosol under cloudfree conditions or indirectly by increased albedo of clouds. Although it appears that calculated and observed temperature trends agree much better with each other when optical aerosol effects are included in global climate models, thus providing some evidence for the significance of the aerosol-climate feedback, those conclusions are still based on rather weak grounds, again largely because of lack of knowledge about the physiochemical properties and distributions of atmospheric aerosol. In particular, the above mentioned model runs were performed only considering sulfate aerosols, which are strongly derived from coal and oil burning. However, several addition-

al types of aerosol, which can likewise be influenced by human activities, are emitted into the atmosphere, such as

- * smoke sunlight-absorbing aerosol, mostly from tropical and subtropical biomass burning;
- * soil dust;
- * organic aerosol, resulting from gaseous organic precursor emissions from vegetation;
- * seasalt particles.

Clouds can provide major pathways for the chemical processing of natural and anthropogenic emissions. While this chemical cloud effect has been studied for a few major components such as SO_2, there are many more soluble and reactive atmospheric constituents whose cloud processing is largely unknown.

Neither the quantities of emissions nor the global distribution of these aerosol are even approximately known, but one thing is clear: they all play important roles in the climate and the chemistry of the atmosphere. And again, also here the main gaps in knowledge may well be in the tropics and subtropics.

The lack of knowledge also concerns the interactions of gas phase species with the aerosols. As an example, in all climate simulations the calculated distributions of sulfate aerosols have been conducted, neglecting potential interactions of anthropogenic SO_2 with the other types of aerosol. This may well mean that much of the sulfur, which is emitted into the atmosphere, may be deposited on other aerosol, such as soil dust and seasalt particles. If that is so, then no additional sulfate particle formation could take place in regions with high emissions of such particles, implying that the sulfate cooling effect may have been substantially overestimated. What is needed most now are measurements of the emissions and global distributions of the various kinds of aerosol, especially in the tropics and subtropics.

Closely connected to what has been said above about the atmospheric chemistry aspects of global change, are biosphere/atmosphere interactions, as many of the chemically and climatologically important trace gases are likewise to a substantial degree emitted into the atmosphere by the biosphere. Besides CO_2 and N_2O, we mention especially NO, CH_4, and reactive hydrocarbons which together have a substantial impact on O_3 and OH concentrations and which are increasingly impacted by human activities.

I propose, therefore, that in future “global change” research substantial attention is given to the tropics and subtropics. This also requires the involvement and training of local scientists who participate in joint field programmes: a strong scientific basis in this part of the world will in future not only benefit progress in science, but will also lead to greatly improved scientific inputs in political decision making.

WHICH ECONOMIC SYSTEM IS LIKELY TO SERVE HUMAN SOCIETIES THE BEST? THE SCIENTIFIC QUESTION

EDMOND MALINVAUD

The purpose here is to establish a framework within which scientists could bring their testimony to the Catholic Church about a highly relevant and much disputed issue. The fate of people very much depends on the institutions which shape societies, and knowledge of this dependence is a scientific question which motivates thought and research. The challenge concerns in particular what scientists can say about which economic system should be chosen.

The testimony discussed here is meant to come from economists and to be addressed to the social teaching of the Church. With this limited scope we shall, first, outline the historical development of the issue; second, describe in broad strokes the main framework within which improvement in scientific knowledge has to be achieved; and third, give some hints about answers to three sub-questions, which are taken as illustrative of what economists discuss.

I. THE STATE OF THE ISSUE

Speaking here of the past development of objective views on our subject will simply serve to remind us of the historical background to the present question and the difficulties which were encountered in producing a scientific attitude towards it. This will be done by four selective glances: at the early history of the literature on the subject; at the hesitations which marked the twentieth century; at the present social teaching of the Church; and finally at a recent message from a few academic economists on how to manage the market economy so as to meet the development objectives of the Third World.

1. *Notes about the early history of literature on the subject*

Explaining and judging the economic system that emerged at the time of the industrial revolution was the main motivation of those intellectuals of the eighteenth and nineteenth centuries who were after a short time called economists. They were striving for objectivity, but they could not meet the standards that modern science would require. Moreover, what will be said in the next part of this paper about the conditions applying today in economics, was already the case to some extent in those times. Only in the last part of the nineteenth century did systematic use of data and rigorous formalisation begin to penetrate the discipline.

However, ideas were progressively taking the shape of theories. Those presented in the main books of, respectively, Adam Smith and Karl Marx, are good examples for anyone who wants to reflect on the positive contents of the two main strands of ideas which inspired the economists of those times.[1] As is well known, the positive assessments which were expressed did not convey the same vision. According to Smith, given the institution of free exchange the pursuit of self-interest leads to a natural order in which prices regulate economic activities and lead to efficient specialisation. According to Marx, capitalism, which had emerged at a particular historical time and provided the most suitable institutional structure of society, was subject to contradictions which would lead to its replacement by another form of social structure. But both Smith and Marx attributed a large role in their respective analyses to the theory of prices.

It was precisely in order to provide the theory of prices with stronger foundations that in the last decades of the nineteenth century a few economists engaged in what was to become a well structured research programme. This programme was pursued even beyond the middle of the twentieth century and resulted in rigorously formalised theoretical models deductively derived from sets of axioms. Such models now serve as inescapable reference points for any serious study of economic systems.

For what will follow we must note that the theory of prices, established in order to provide foundations for studies of the whole economic system, made only informal references to facts. But, mostly for other purposes in economics, a systematic use of statistical data was also needed. Starting in the first decades of the twentieth century, another important research pro-

---

[1] A. Smith, *An Inquiry into the Nature and Causes of the Wealth of Nations*, 1776; K. Marx, *Das Kapital*, Band I, 1867, Band II, 1885, Band III, 1894.

gramme was initiated. It later developed into establishing an inductive methodology which sought to be appropriate to the conditions within which quantitative economic knowledge can be reached.

2. *Hesitations in the twentieth century*

The feasibility of the socialist planning of production and distribution was, by as early as 1900, the subject of heuristic discussions. Socialist thinkers claimed that whatever the market system could do could also be done by intelligent planning, which could even do things better, at least in terms of equity and fairness.

This basic insight became the subject of what was called 'the economic theory of socialism'. The theory used clean mathematical specifications, and in particular the theory of the general competitive equilibrium, for the representation of the market economy, in addition to another somewhat similar model which supported the instinctive perceptions of socialist thinkers. Around 1960, three broad conclusions were drawn from this theory. First, that it is precisely under the conditions which make the market system work best that socialist planning could also work well, and perhaps even better. But, second, that these conditions were not realistic – the theory had neglected a crucial difficulty in our complex economies, namely the pervasive imperfections of information, of private agents, and of governments. Third, that this difficulty was probably even more damaging for economies run by state planning than for market economies.

Ideas were also evolving in the less formalised schools or branches of economics, particularly in those trying to draw lessons from economic history. As a significant example, I may mention here the hopes entertained by many in the immediate post-World War II period, notably by a number of Christian thinkers: with less involvement of the state than was the case in the Soviet Union, economic planning was feasible in democracies. Such an approach, it was thought, could install economic systems which would be more stable, more efficient and more favourable to solidarity than the systems that had prevailed during the inter-war period. Although fewer and fewer economists shared these hopes over the subsequent decades, planning was still considered as a possible option.

In October 1963 the Pontifical Academy of Sciences held a study-week on 'The Econometric Approach to Development Planning'.[2] It had been

---

[2] *Pontificiae Academiae Scientiarum Scripta Varia*, N° 28, vols. I and II, 1965.

organised by the statistician and Pontifical Academician, Boldrini, and was attended by eighteen rather well-known economists, including some who were very involved in planning methods. These economists did not agree with each other fully and the debate was often tense. However, they were able to issue a common 'Final Statement' printed at the end of the proceedings (which, by the way, ran to more than 1200 pages). This statement deals with a number of points, for instance with the role of the then newly-born discipline of econometrics and with useful research directions. But it is indicative of the ideas of the time that the possible comparative advantage of the market system in ensuring efficiency in the allocation of resources is not mentioned in the 'Final Statement'. Just one paragraph comes close to questioning the ability of governments to plan economic development. Its main sentences run as follows:

> Our discussions also made clear the need for a better understanding of the capabilities as well as the limitations of various instruments of economic policies which governments can use in the pursuit of their short and long-run goals. Research on the nature of the instruments available has been neglected...This neglect has led to the adoption of goals that could not be attained by means of the available instruments and to overestimating the effectiveness of some instruments. In short, more research is needed into what governments can and cannot do in trying to foster economic development and stability.

In the two last decades of the twentieth century, prevailing ideas moved at an accelerating rate away from confidence in governments' claims to control the economy or even simply to intervene in it. Roughly speaking, the main reason was experience rather than deduction: the failure of Soviet planning became manifest; even in OECD countries people became more and more aware of costly inefficiencies in the operation of the welfare state, and more generally in public economic management; and the internationalisation and globalisation of economies made claims relating to central national direction less and less credible.

3. *The social teaching of the Church*

Although the social teaching of the Church had developed down the ages ever since the Bible, the encyclical *Rerum Novarum* (1891) of Leo XIII marked a revival in Catholic reflection on the socio-economic system. Concerned about the social problems of industrial countries, the

Pope repudiated the two ideologies of liberal capitalism and socialism. Starting from the premise that 'capital cannot do without labour, nor labour without capital', he argued for a return to a Christian environment recognising both private property and the rights of labour, which had to be realized by the social policy of the state in collaboration with trade unions. In *Quadragesimo Anno* (1931) Pius XI went further in suggesting the establishment of a new socio-economic system in which the causes of conflict between labour and capital would be strongly mitigated by the use of a corporative system. The development of Catholic social doctrine continued, thanks in particular to close collaboration, on the one hand, with Catholic social movements, and on the other with experts in the social sciences.

In 1991 the encyclical *Centesimus Annus* displayed the overall benefit to be drawn from the recent emergence of a higher degree of consensus in the academic community of economists when, concluding Chapter IV (the longest of all), the Pope wrote:

> Is [capitalism] the model which ought to be proposed to the countries of the Third World which are searching for the path to true economic and civil progress? The answer is obviously complex. If by "capitalism" is meant an economic system which recognizes the fundamental and positive role of business, the market, private property and the resulting responsibility for the means of production, as well as free human creativity in the economic sector, then the answer is certainly in the affirmative, ...But if by "capitalism" is meant a system in which freedom in the economic sector is not circumscribed within a strong juridical framework which places it at the service of human freedom in its totality, and which sees it as a particular aspect of that freedom, the core of which is ethical and religious, then the reply is certainly negative (n. 42).

This is not the place to make even an abridged summary of this rich encyclical, still less, of course, to seek to speak about the whole present social teaching of the Church on economic systems.

4. *A message from scientists about the public management of economies*

Published in 1997 by Clarendon Press, Oxford, for and on behalf of the United Nations, *Development Strategy and Management of the Market Economy* presents and explains the conclusions of a few academic economists about recommendations to be made for the countries of the Third World.[3] Here are two extracts from the short 'foreword':

> Public policy discussions should begin with the recognition of the essential role that the markets play in the efficient allocation of resources. International openness, as well as free domestic movement of goods and factors of production, are crucial. Many of the mistakes in earlier development policies arose from an inadequate appreciation of the role of markets. However, in some cases, markets either do not exist or fail to operate effectively – because of imperfect information, structural rigidities, insufficient infrastructure, or far-reaching externalities. Moreover, demands of distributive equity may end up being neglected in market allocations with unequal resource endowments. Deficiencies of these kinds can be particularly pervasive in developing and transitional economies.
>
> Instances of market failure do not imply that the use of markets should be abandoned, or that liberalization and deregulation policies are unnecessary in those economies which have tended to cramp the effective operation of markets. On the contrary they highlight the need for public policies to be informed by rigorous analysis, particularly of the nature and causes of likely market failures. Nor should we assume that governments can always eradicate market failures through intervention. Development experiences point to a wide range of government failures as well, especially when the measures aim at supplanting market signals rather than modifying them appropriately.

After having insisted on the fact that 'development is a long-term endeavour' and that the sustainability of any development process can be endangered by macroeconomic instability, the 'foreword' concludes:

> These general ideas served as the point of departure for our examination of the appropriate combination of the government and the market in the construction of development policies. There is much complementarity between these two fundamental components, and it is sensible to think of a partnership between the government and the market in the formulation and implementation of successful development strategies.

---

[3] E. Malinvaud, J.-C. Milleron, M. Nabli, A. Sen, A. Dasgupta, N. Stern, J. Stiglitz, K. Suzumura.

II. CONDITIONS SURROUNDING POSSIBLE IMPROVEMENTS IN SCIENTIFIC ANSWERS

In order to present explanations for the present state of the issue and to suggest how fuller scientific answers might be reached, we shall state here a few propositions about the conditions under which advances in knowledge of the question have to take place.

1. More than economics is involved, because, first, the relevant concept of 'the economic system' is broad and concerns legal, political and social institutions besides purely economic ones; because, second, what is meant by 'serving human societies' covers not only economic aims but also achievements with respect to such values as individual liberties and capabilities; and because, third, the range of feasible achievements will depend on such non-economic factors as population, the availability of natural resources, technological progress, political feasibility, the competence and devotion of governments, social cohesion, peace, and so on. Economists are of course aware of these various aspects, but they do not have full competence in dealing with them.

Such being the case, natural scientists might believe that the rational response to what turns out to be a multidisciplinary challenge ought to come from a multidisciplinary research programme. But in actual fact the implementation of such a response is highly problematic because colleagues specialising in other disciplines are seldom keen to enter a programme of that sort. They are not really interested in the purpose of the research; their knowledge is not geared to being useful for the purpose. Take for instance the question of knowing how the diffusion of the new information technologies will interact with the functioning of various economic systems: broad views about the issue are present in the press and known by economists. Would a scientist, an expert in the development of those technologies, bring relevant additional knowledge? Or take the question of knowing what could be the contribution of sociologists to the research programme, which has to come up with positive proposals rather than with radical critiques of whatever happens to exist, a programme, moreover, which stands at an intermediate level between the study of micro social structures and broad universal visions.

The opposite approach, namely for economists to appropriate the study of non-economic aspects and thereby to incorporate non-economic features into their analyses, is followed more frequently: this applies at the present time particularly to the study of political aspects, but it is not limited to the extension of this domain claimed by some economists. Such an extension is exposed to two dangers. The introduction of non-economic factors may be quite naive. If it is not, economists may rely too much on assumptions and modes of analysis which are more justified at the core of their domain than outside it. For instance, they may overestimate the real scope of cases in which self-interest is the dominant motive behind action.

Whatever the case, a tension will remain between the judgment of economists and what could come from the competence brought by other scientists, a tension which will eventually be fruitful only if it actually manages to stimulate interchange.

2. Social scientists do not strive only for objective knowledge, but also for the formation of ideologies and social norms. This is not surprising because most of those who have undertaken research and analysis into social phenomena have been motivated by concerns about some kind of social malfunctioning. They originally intended to investigate the problem and hoped to find ways of coping with it. But before seeking to engineer a remedy they have to persuade others about the existence of the problem, about the value of their proposals, about the need to join movements which will act with them. Natural scientists are also inclined to become the advocates of particular policies, but precisely because their disciplines are more ‘exact’, the distinction is more easily made than in social sciences where there is often an ambiguity between the two roles of scientific research and social action.

It is clear that economics increasingly tends to avoid the confusion: our discipline seems to be definitely more prone than other social sciences to the pure search for objective assessments. However, when they approach discussions about the economic system, many economists still have difficulty in separating the positive issues of scientific knowledge from normative issues. The difficulty is particularly apparent with those who have strong social motivations, or who, working in cooperation with people belonging to other social disciplines, are naturally led to adopt practices which are common to those disciplines.

3. Most academic economists shy away from approaching research closely connected with the choice of economic systems. This is a respectable position because this choice is such a complex question that the objectivity required may appear paralysing, particularly for scientists working on radically different topics within economics. The fear that they will be dragged into the realm of ideological conflict also plays a role in bringing about this approach.

But this respectable position creates a perverse self-selection of the group of academic economists who take part in debates about the economic system. Usually this group has less exacting standards of rigour. This perverse selection is not only a factor of direct disturbance but is also indirectly damaging with regard to the visibility of the 'new political economy' school, which is otherwise an entity much to be welcomed.

The school is made up of economists working at the frontier of political science on issues which involve both economic knowledge and a good understanding of how the polity functions. Most of its contributions deal with current economic policy rather than with the choice of economic systems. Unfortunately, benefiting from the scientific recognition of the school, more and more people claim in unwarranted fashion to speak under its banner, even on broad issues. This creates a new source of confusion.

4. *Economics is better at detecting dilemmas than at finding the right solutions to them.* Economists are often criticised in such terms by those who address them. Confronted with a question, especially a burning question, the typical economist patterns his or her answer according to the 'on the one hand...on the other hand' opposition. Subsequently, he or she is usually unable to offer a clear conclusion. This attitude on the whole reflects the real difficulty of the question and the limitations of economic knowledge.

Take for instance any of the major issues about the welfare-state institutions of OCDE countries (old age pensions, health care schemes, unemployment insurance...). You will find that, on the one hand, the concerns of the early promoters have been well justified: these institutions do indeed bring social benefits to the population. But, on the other hand, in their achievement of their well justified objectives, present institutions are less efficient than was expected: they are not selective enough and they are excessively exploited by people who learn how to turn the system to their own personal advantage, far beyond the original purpose of the system (basically, this follows from the fact that individuals benefit from 'asymmetries of information': some of their characteristics and some of their actions are hidden from welfare institutions). There is thus a trade-off between the extent and form of social protection and its cost in terms of the economic performance of the country. In order to decide what to do, you need accurate quantitative assessments of the true benefits and costs under alternative set-ups. But such assessments are very difficult to establish – what can be provided leaves wide margins of uncertainty, as we shall see when discussing below the question of how to select an appropriate level for the minimum wage.

At this point, in order to have a good grasp of the subject of this paper, we cannot but engage in a detour and discuss the methodology of economics.

5. Knowledge in economics comes from original combinations of induction and deduction. This has important consequences for what the discipline can achieve. The originality of the approach, in comparison with the natural sciences, is due to major differences in empirical sources.

Whereas economic phenomena are complex and more exposed to changes than is the case with natural phenomena, the scope for experimentation in economics is rather limited. But economics draws knowledge from two sources of evidence: it not only involves external observations of phenomena appearing at the individual or aggregate level (statistical observations), but it also draws advantage from direct, or equivalently 'internal', knowledge of a large part of the domain to be investigated. This direct knowledge involves (i) the constraints and motives ruling individual economic activities, (ii) the interactions between economic agents when they contract or act within the confines of pre-existing contracts, and (iii) the system of legal or informal institutions within which activities and interactions take place.

Separately seen, each one of these two sources of evidence is too poor to be sufficiently revealing for most of our scientific purposes. But considered jointly they bring richer information. Indeed, internal knowledge is mainly qualitative; what can be deduced from it alone is too vague. External observation bears on the results of complex phenomena, involving too many causalities to clearly exhibit the force of each cause, except within specific models which incorporate what can be derived from internal knowledge.

The professional skill of economists in relation to each subject tackled by their discipline specifically involves how best to articulate this combination between the deductive study of accepted models and the appeal to new external or perhaps internal evidence, which will make these models more informative – i.e. more specific (accepted models incorporate not only what comes from internal knowledge, but also what was already learned from the previous processing of external evidence).

In order to move ahead and suggest more concretely how economists try to tackle, and address themselves to, the main questions raised at present by the choosing of economic systems, we shall turn our attention, by way of a brief introduction, to the consideration of three cases which are taken to be illustrative: the proper concept of the market economy; the extent and challenges of globalisation; and the minimum wage as a simple example of questions which are more generally raised by the welfare state.

III. Three Substantial Topics

1. *The concept of the market economy*

Actual market economies are very complex objects and differ from one another in a number of respects. Research on them involves a large number of aspects: their market structures, with for instance the degree and form of concentration of enterprises or trade unions; the legal, regulatory and customary rules under which they function; how they develop or adapt to changes in their environment, and so forth. Research approaches and methodologies also vary from the most tightly formalised forms, with their axioms and mathematical models, to the most heuristic forms by which to comprehend new real phenomena or challenges, such as the transition to market economies of the central and eastern European countries. In order to illustrate this variety we must be selective here and focus on only two research lines: the highly formalised, which has already been introduced in Part I, and the highly heuristic, which deals with an important recent new form of contrast between two large market economies – Japan and the USA.

1. As we have seen, the discussion about socialist planning during the first half of the twentieth century referred to an ideal vision of the alternative offered by the market economy – the vision conveyed by the formalised theory of the general competitive equilibrium. The exact scope of this theory is now much more fully understood because of two strands of research. The first seeks to make the theory as rigorous and as general as possible. The second strives to study how robust the theory is by analysing deviations from its basic hypotheses in order to show why thetheory is incomplete as a representation of actual market economies, a premise to providing alternative models. In both cases the deductive approach dominates.

For our present purpose we may select two broad conclusions produced by the second strand of research. Firstly, the dynamic stability of actual economies appears questionable because rigorous attempts at formalisation of their dynamic behaviour have revealed many potential sources of instability. Since the middle of the twentieth century most research developments on the theory of the general competitive equilibrium have been concerned with time and uncertainty: the market equilibrium is meant to involve not only immediate actions – exchanges and prices – but also the plans of agents in relation to the future, the prices applying to such intertemporal exchanges as loans, expectations about future actions, and exchanges and prices in an evolving economy hit by random shocks. We understand that the research programme is wide. We are not surprised to learn that unstable evolutions are often found which may rationalise what is observed in the real world. We may hope that theory will help us to achieve a greater control of actual economic disturbances.

Secondly, market participants do not all act on the basis of the same information, and the consequences of the actual asymmetries of information are pervasive. In particular, they explain why contracts cannot deal in advance with all contingencies – contracts involving the future are incomplete. This applies to the relationship between a supplier and a client, between an employer and an employee, and so on.

These two broad conclusions are interrelated, in particular in explaining the reasons for, and the consequences of, price and wage rigidities. The second strand of research, at a more general level, brings to the fore the importance of the legal and judiciary system which governs the implementation of contracts. It also provides arguments in favour of the existence of some market regulations, some public provision of collective services, and some deliberate public economic policies.

2. Our present knowledge of the market economy is not based only on the reflections conveyed by the discussion of formalised theory expressed in mathematical models. It also derives – and probably to a great extent – from lessons empirically learned from experience. We have already pointed to the determinant role of this second source of knowledge (at the end of section I.2). Following along the same line with an illustrative example, we shall now dwell upon some of the reasons which lay behind a phenomenon which led to a complete reversal of opinions, in less than a decade, regarding the relative performances of the Japanese and the US economies.[4]

Ten years ago, surveying the US economy, which was at that time dogged by slow productivity growth, corporate downsizing and record budget deficits, many American observers looked with envy to Japanese growth levels and were inclined to think that they were related to the centralised coordination of productive activity (complementing market incentives) in a context where large corporations were run by command and control, with

---

[4] We draw from a speech of Professor L. Summers, now Secretary of the US department of the Treasury, at the American Academy of Arts and Sciences, 14 April 1999. See the Academy *Bulletin*, November-December 1999, vol LIII, N° 2.

relationship-driven debt finance rather than recourse to equity issues on the capital market, and an informal rather than formal enforcement of contracts. After the high US growth rates of the last decade and the stagnation of the Japanese economy, which is now embroiled in a deepening financial crisis, the same observers have reached the conclusion that the US model was better equipped to take advantage of the overall change induced by new technologies and globalisation than its Japanese counterpart.

Three reasons are put forward in order to explain why the US economy was better prepared. Firstly, when creativity and innovation are the greatest potential sources of wealth, economies need systems in which access to finance and support depends less on where you are from and more on where you are heading: the openness of the American financial system in such a case is a definite advantage. Secondly, when economic values often change quickly, in particular because technology is in a constant state of flux, the economic system ought to be flexible enough to permit companies to go quickly through painful re-engineering and restructuring, developments which have to reflect competitive realities. Thirdly, in a globalised world family links have limited reach, whereas formal contracts and the American preference for rules over understandings and for law over custom permit large-scale opportunities to be seized very quickly.

Ex post rationalisation, which can be perceived in these arguments, is no guarantee for accuracy in the prediction of future developments. However, the few characterisations which have been made refer to different features in most modern market economies, features which may well be strategic in explanations of what these economies can achieve.

Having now in mind both formal theory and the heuristic type of approach to which has just been referred to, we may still ask ourselves whether economists give sufficient attention to an important dimension of the neo-liberalist discourse. This last preaches democracy as well as free markets. It sees the two aspects as being complementary and it is obviously successful in inspiring some of the modern choices about the socio-economic system. Intuition suggests that whether and how such a complementarity between markets and democracy ought to hold is an important issue, particularly for the social teaching of the Church.

2. *The extent and the challenges of globalisation*

The importance of the international exchange of goods and ideas is by no means new. However, after the contraction imposed by the Great Depression and the Second World War, this importance has increased so much during recent decades that people often entertain the vision of a single world, within which economic activities would freely develop under a single and uniform set of rules with no distinction according to location. Reality is, of course, still rather different, particularly with regard to the employment of labour. But reference to a global economy which corresponds to this vision is relevant in discussions about the future economic system.

The principle of the unity of mankind makes the vision attractive. But when we realise that, for a long time to come, political globalisation will not be achieved, the matter becomes less clear. Interacting connections between the global economic system and a diversity of national political systems ought then to be defined. Even if we limit attention to the case of a global market economic system, the interacting connections with political systems constitute a complex issue because of the importance, in the market economy, of the legal and judicial system, of market regulations, and of economic policies, and this for the reasons suggested in the foregoing section. Given the difficulty of the general issue posed in this way, it is not surprising to learn that research about globalisation in economics deals with much narrower issues, among which the following, which we will now consider in turn.

1. Do national economies benefit from insertion into the world economy? Insertion into the world economy imposes constraints, against which public opinion often rebels, both in less developed and in advanced countries. But insertion also opens up opportunities for countries which have comparative advantages to extend their activities. The conclusions now reached by most economists who have studied the issue is based largely on observation of what has happened throughout the world over the last five decades.

Overall, the benefits offered by new opportunities have been found to far outweigh the costs imposed by market constraints: countries which have opted for an import-substitution strategy, favouring the stimulation and protection of national productions, have performed systematically less well than those which have opted for free trade and export promotion. However, the explanation for the tremendous disparities between national performances and national developments in terms of standards of living require greater scrutiny. It has been found that the main responsibilities for such disparities are of a national character: most differences in growth records reflect differences in the quality of government and in the soundness of the strategic policy choices which have been made, including those concerning international trade. But trends in the global demand and supply of commodities have also played a part, in interaction with trade policies. Moreover, we cannot expect the benefits and costs of globalisation to be evenly distributed between countries and within countries. In other words, a simple answer to the question raised can hardly suffice.

2. Has the globalisation of financial markets now gone too far? We do not find in economics at present a clear answer to this question, which some economists even tend to see as being purely academic (was it possible to resist the trends towards an increasing international mobility of capital and towards the establishment of a less distorted balance of powers between managers and shareholders in large companies?) Two concerns seem to be widely shared at present. In the first place, increases in the geographical distance between labour and capital within large international corporations are socially unhealthy. In the second, the notorious instability of financial markets might become more dangerous with globalisation. In both cases these concerns call for serious examination, and possibly the discussion of remedies. Convincing scientific responses to the challenge posed by the first concern would have to draw upon all parts of the methodology of economics and to look extensively beyond the confines of economics.

There is an obvious connection between a research programme on the instability of globalised financial markets and the programme to which we referred earlier – namely on the more general stability of equilibria in market economies. However, financial markets are special because they involve only minimal transaction costs, which have, moreover, sharply decreased during the last two decades. This implies, in particular, an increased participation of agents – called ‘arbitrators’ or ‘speculators’ – who, in trying to take advantage of small price disequilibria, help to make the markets more efficient, although they may also make these markets less stable. It thus appears that a special research programme is required in order to improve upon the overly heuristic answers now given to questions raised by the second concern mentioned above.

3. *The minimum wage*

1. Fifty years ago Western European countries chose a mixed economic system in which on the one hand freedom of contracts prevailed, with markets ruling exchanges and the formation of prices. But on the other hand, a public welfare state was established which aimed at the regulation of the macro-economy and at a redistribution of incomes to the benefit of those who are temporarily or permanently in need. The experience of recent

decades has showed that such a mixed system has worked less well than was expected. It has proved to be more costly than envisaged because in particular it has involved greater expenditure than was justified by the objectives of social policies. It has been less effective in redistributing incomes. Hints were given about the reasons for such deficiencies in section II.4.

Thus the future of welfare-state institutions poses challenging problems. Such being the case, it is natural to invite specialists to provide objective assessments of the costs and benefits of alternative welfare-state arrangements. The assessments in question would give measures of the trade-offs between costs and benefits, or between degrees of satisfaction of various objectives. Unfortunately, what is objectively known is uncomfortably vague because of large inaccuracies in the establishment of relevant economic and social parameters. The econometric difficulties which explain why this is so appear in the particular case of the minimum wage, here taken as a significant example.

2. Clearly, the existence of minimum wages in many countries derives from the perception of a need to prevent cases in which the weakest employees are exploited by their employers. Once this is accepted, the question of the appropriate level of the minimum wage immediately follows. A excessively high level will prevent the employment of the less productive workers, those who are judged by potential employers to have a lower productivity than the cost to be borne of their labour (the wage plus whatever taxes the employer has to pay because of this employment). We must also take account of the fact that the unemployed suffer not only from a lack of labour income but also from a feeling of exclusion and personal failure. A minimum wage level which is so high that it has a significant impact on employment is thus likely to have a more important social cost than the social benefit produced by the prevention of exploitation.

In order to help in the determination of the appropriate level, economists ought, therefore, to estimate the trade-off between increases in the minimum wage and increases in unemployment, which become more and more important as the minimum level is raised. A brief explanation of the main difficulties of the assessment may be the best way by which to convey a sense of the real importance of the problem.

Firstly, econometric measurement encounters difficulty most often in its attempts to allocate observed results to the various causes that play a part and combine their effects. This is an unfortunate fact which arises from the scientific conditions in which econometrics has to operate (see section II.5). Although different kinds of data sets can be, and have been, used, in all cases the identification of effects to attribute to the level of the minimum wage turns out to be problematic.

Secondly, some economists attribute to minimum wages an important indirect role in generating overall unemployment: the protection of workers is said to contribute to making all workers less willing to accept 'the verdict of the market'. Where minimum wages are generous, it is affirmed, workers more generally obtain excessively high wages, which, so the argument goes, generate unemployment. But the force of such an indirect effect is not invariant. It very much depends on: (i) the way in which the whole wage scale is determined; and (ii) whether an overall increase in wages reduces or does not reduce employment. An accurate characterisation of this indirect effect has to distinguish between quite a few different cases.

Thirdly, the trade-off between the level of the minimum wage and employment of the unskilled has an important time dimension which may be neglected and ought not to be. If the minimum wage is lowered, the impact on the income of the workers concerned will be instantaneous, whereas the increase in the chances for unemployed unskilled people to find jobs will be slow – it will appear progressively over a period covering a decade or more. But where levels of the minimum wages are high, changes in these levels should eventually have quite significant effects on the employment of the category of persons affected by these changes.

Notwithstanding these various causes of inaccuracy, knowledge progressively improves and accumulates. In particular, we know that the appropriate level of the minimum wage for a group of workers varies with the productivity of those workers. This is a particularly important consideration when one comes to the geographical dimension of regulations. In some countries or other large areas labour productivity varies a great deal from one region to another. The application of the same uniform minimum wage in all regions is likely to foster persistent unemployment in the less productive regions. We have recurrent evidence, coming from external observation, which points to this conclusion.

SUSTAINABILITY: PROSPECTS FOR A NEW MILLENNIUM

PETER H. RAVEN

> Humanity stands at a defining moment in history. We are confronted with a perpetuation of disparities between and within nations, a worsening of poverty, hunger, ill health and illiteracy, and the continuing deterioration of the ecosystems on which we depend for our well-being. However, integration of environment and development concerns and greater attention to them will lead to the fulfillment of basic needs, improved living standards for all, better protected and managed ecosystems and a safer, more prosperous future. No nation can achieve this on its own; but together we can – in a global partnership for sustainable development. (Agenda 21, Earth Summit; Sitarz, 1993).

The noted scientists and technologists who gathered for the Congress of Arts and Sciences in St. Louis in 1904 would not have understood the meaning of those ringing words. Instead of worrying about global inequities or the destruction of the environment, they were delighted with the prospects for a world in which the possibilities for progress seemed virtually unlimited. More than a century after the introduction of the steam engine, the fruits of the Industrial Revolution had become evident on every front, and the United States was looking forward to a future of international leadership. Taking my cue from the St. Louis Congress, I shall focus many of the following remarks on the role of the United States, but shall eventually broaden that view to encompass the world, a world in which the influence of the United States and other industrialized nations is pervasive.

When the delegates assembled in 1904, they would have been mindful of the death of Queen Victoria, who had given her name to an era that had witnessed the most extraordinary scientific, technical, and industrial advances that the world had known to that point. The St. Louis World's Fair itself was celebrating not only the growing outreach and power of the United States, but also the broad vision of a diverse world that seemed to hold so much promise for the future. Theodore Roosevelt, the youngest American president, was in the White House, later to win the Nobel Peace Prize for his role in bringing about the end of the Russo-Japanese War; about to become the first American President to travel outside of the country, when he visited the construction site for the Panama Canal (completed in 1914); and poised, in defiance of Congress, to send the American Navy around the world as a show of national strength (1908).

At the same time as Americans were so excited about the prospects for the development of the airplane, of the automobile, of new modes of communication, and all of the other inventions that promised so much for the future, a few of them had also begun to realize that the world was not as unbounded and limitless as it once had seemed. Explorers had reached the far comers of the Earth, and knowledge was pouring in about its lands and its peoples: we increasingly knew what was there. Fredrick Jackson Turner, later to become America's preeminent historian, had announced the closing of the frontier, an idea that was to have great influence on collective visions of the world in the early years of the century. What were the turn-of-the-century antecedents of ecology, of sustainability, and of biodiversity – concepts that are now intellectual landmarks on the topography of the twenty-first century, but virtually unknown a hundred years ago?

The World Then and Now

At the turn of the century, after more than a hundred years of the Industrial Revolution, the global population stood at approximately 1.65 billion, with about 74 million people in the United States. In about four months, an event to be officially "celebrated" on October 12, 1999, there will 6 billion of us, including a billion added within the past 12 years, and the billion before that in 13 years. There are at present just over 270 million people in the United States. Human expectations have risen continuously over the course of the century, while the global population has more than tripled; consequently, the level of consumption in the industrialized world has risen to heights undreamed of just a few decades ago. Changes in the biosphere also have been unprecedented, with a major proportion of them having occurred during the past 50 years (Turner, 1990). Over this period, and for the past few hundred years, technologies have been invented and deployed, and the world has in what is geologically an instant of time been converted from a wild one to one in which human beings, one of an estimated 10 million species of organisms, are consuming, wasting, or diverting an estimated 45 percent of the total net biological productivity on land and using more than half of the available fresh water, locally at rates that clearly cannot be sustained for long. The properties of the atmosphere have been and are being substantially changed by human activities, almost all major fisheries are under severe pressure, and habitats throughout the world have been decimated, with populations of alien plants and animals exploding and causing enormous damage throughout the world, while species extinctions have reached levels unprecedented for tens of millions of years. Despite the optimistic tone set by the Earth Summit declaration quoted above, with perhaps 3 billion additional people joining our numbers over the next half century, we will clearly have an increasingly difficult time in maintaining our current levels of affluence or in achieving the lofty goals which our historical progress seems to have made available to us. The scales and kinds of changes in the Earth's life support systems are so differenent from what they have ever been before that we cannot base our predictions of the future, much less chart our future courses of action, on the basis of what has happened in the past (Vitousek *et al.*, 1997).

As Bill McKibben has outlined in his book “The End of Nature” (1989), we have arrived at a time when human beings are effectively managing the whole planet, for better or worse. The end of nature as he understands it is the end of nature functioning independently of human beings. This is the vision that was explicitly explored in the outstanding collection of essays, “Uncommon Ground” (Cronon, 1995). Specifically, in the field of conservation, those organisms that survive will do so because human beings manage the Earth's resources in such a way that this is possible; those that are lost will be lost for the same reason. The pressures we exert on global ecosystems are so extensive that their future is up to us. For these reasons, it has become clear that we clearly are living in the most difficult and challenging times that humanity has experienced. How did we get to this point, and what have been some of the warning signs along the way?

A mere 10,000 years ago, when crop agriculture was first developed at several widely scattered centers both in the Old World and the New, several million human beings, far fewer than the number of people who visit the museums of the Smithsonian Institution annually, populated the world, at about the density of Aboriginal peoples in Australia before European contact. The availability of larger quantities of food, on a more dependable basis that had existed before that time, created conditions for the rapid growth of the human population to an estimated 300 million at the time of Christ, a number that held more or less steady for a thousand years, grew to 1 billion around 1800, reached 2.5 billion by 1950 and will, as I mentioned above, reach 6 billion in the present year, 1999. As human numbers have grown, their impact on the environment increased also, regional evidences of overgrazing or deforestation having been regarded with dismay by some people ever since Classical times. It has been during the period of the Industrial Revolution, from the mid-eighteenth century onward, however, that the evidence of widespread human domination of the natural environment has grown so rapidly and become so obvious as to affect the world view of every person concerned with the future.

The Growth of Environmental Consciousness: Before 1900

Following Columbus' landfall in the New World five centuries ago, at a time when the global population was less than a tenth of what it is now (about 500 million), waves of people from the Old World colonized the newfound lands and grew to great numbers and great power. The same *phenomenon occurred* throughout the world, as colonial expansion and the extension of often unsustainable forms of land use rapidly changed the face of the continents (Grove, 1995). As Andrews (1999, p. 18), put it, "Colonization... was among other things an environmental policy". The ways in which relatively unspoiled lands were rapidly changed by the practices associated with colonization, and the ideal visions of such lands that persisted in the minds of Europeans far longer than they did on the ground, had a great deal to do with our collective understanding of the limited nature of local and ultimately global resources (McCormick, 1989). By the 1850s the problem of tropical deforestation was already being viewed as a problem on a global scale, and one that urgently demanded correction. Although less emphasized in the latter decades of the nineteenth century and the first half of the current one, the powerful metaphor of the destruction of Eden proved an enduring and influential one.

In Colonial America, the collective vision was one of an endless cornucopia of forests and meadows, rich in natural resources to be exploited – the destruction of the wilderness and the taming of nature were widely-accepted as desirable goals. The image of nature in all of its wonder and abundance, and the deep and abiding love of the land that Americans generally share, however, also. have their roots in this early history: the land seems inexhaustible, rich, and nurturing beyond our wildest dreams. As

Wallace Stegner (1980) put it, “While we were demonstrating ourselves the most efficient and ruthless environnient-busters in history, and slashing and burning and cuffing our way through a wilderness continent, the wilderness was working on us. It remains in us as surely as Indian names remain on the land. If the abstract dream of human liberty and human dignity became, in America, something more than an abstract dream, mark it down at least partially to the fact that we were in subtle ways subdued by what we conquered”. In these words, Stegner has captured the essence of the ethical, moral, and religious overtones to environmentalism, which are fundamentally important to our perceptions of the field, and underlie our hope of progress in the future. Although much of what we say and do is materialistic and operational, the reasons that we do it lie within ourselves.

Even in colonial times, some began to take seriously the evidence of threats to the bounty of the land, and to view the profligate use of natural resources as a problem (Nash, 1982; Shabecoff, 1993; Andrews, 1999). However, it was not until the advent of industrialization, roughly from the 1830s onward in America, that massive changes in the landscape began to become evident on many different fronts. In a relatively few decades, from the mid-nineteenth century onward, most of the prairies were cleared, the remaining great forests were cut, and farms and, increasingly, cities were established everywhere in the land – the activities noted so poetically by Stegner were carried on apace. In addition, it has gradually become clear that “nature” is a profoundly human construction: it can never be separated fully from our own values and assumptions (Cronon, 1995, p. 25).

Increasingly alarmed by these trends and their perceived effects on the future productivity of the land, influential writers and public figures, mostly living in the cities of the East, began to call for the preservation of some of our national wildlands, especially in the West: the sense of passing of the wilderness ultimately had a powerful effect on the national imagination. Ralph Waldo Emerson and Henry David Thoreau re-defined our relationship with nature, laying the foundation for modem environmentalism and the concept of sustainability. At the same time, Charles Darwin, by placing the human race clearly in the biological context of its evolutionary history, helped substantially to break down the dichotomy that had been so generally accepted earlier between people and nature. Subsequently, George Perkins Marsh, America’s first true environmentalist, understood well the concept of the balance of nature and brought it to the attention of a wide public, basing his appreciation on his knowledge of his native state of Vermont, as well as on his wide travels in the Mediterranean basin and elsewhere; his 1864 book, *Man and Nature; or, Physical Geography as Modified by Human Action* is a classic both of environmentalism and of ecology. Marsh saw clearly that the destruction of nature could not be sustained, and pointed out the need for care in the management of our resources for the sake of future generations. America's first national park, Yellowstone, was established the same year that Marsh's book was published. Another notable and far-sighted early experiment in re-defining the relationship between man and nature was the establishment of the Adirondack Forest Preserve, later the Adirondack Park, by New York State, in 1885.

At the same time that concern about nature, and especially about the fate of the Western lands, was growing, another important trend was greatly influencing the development of environmentalism. The explosive growth of cities and the increasing urbanization of the population brought widespread urban pollution, along with the development of a new way of life that differed remarkably from that of the countryside: the same trend that had accompanied the advances of the Industrial Revolution earlier in England and elsewhere in Europe. The new urban-centered life, and the development of the many remarkable institutions that it made possibe, provided an abundance that led to a growing equality and equity, but also gave rise to many new problems concerning the conditions under which people actually lived in those growing cities, swollen by the ranks of immigrants seeking a new life in America. Thus nearly 13 million immigrants came to the United States between 1890 and 1910, the great majority of them living in cities, where they were joined by large numbers of people moving from the farms. Coal dust, smoke, and toxic chemicals, open sewers, uncertain and often polluted water supplies, crowded and unsanitary toilets – these were the commonplace experience of urban dwellers at the turn of the century. The collective realization of what the awful crowding in cities, the squalid living conditions and urban pollution meant to the lives of people became, along with the protection of natural resources, a second element of fundamental importance in the formation of American environmentalism (Andrews, 1999, chapter 7), one that ultimately contributed enormously to the strength of the modem environmental movement (Gottlieb, 1993).

The Science of Ecology

The essays that were presented by Oscar Drude and Benjamin Robinson in St. Louis in 1904 revealed an ecology that was in its earliest stages of development. Their papers were mainly concerned with plant distribution and the organization of plant communities around the world, with no reference to any of the dynamic concepts that have come to be associated with the modem synthetic science of ecology a century later. The term “ecology” had first been proposed by the German biologist Ernest Haeckel in 1866, but Haeckel had no particularly novel insights about the field. In developing the concept, he was referring to the web that linked organisms with their environment, an idea directly related to the notion of “natural history” as it had been understood earlier. Essentially, the science of ecology is one that has developed entirely in the twentieth century.

At first, it was the study of plant ecology, and the relationships within plant communities that dominated ecology; but oceanography, linmology, and other disciplinary approaches now part of the field were developed during the same years. Efforts to chart the limits of plant distribution and to understand those limits in a historical sense were pursued actively, with terrestrial animal ecology coming along later (McIntosh, 1985). F.E. Clements, who had served as secretary for the ecology section of the 1904 St. Louis meeting, became an important pioneer and leader in the development of more dynamic concepts, and helped to lead ecology away from its roots as a purely descriptive discipline. During the same years, H.C. Cowles, at the University of Chicago, played a seminal role in the development of the science by adding his valuable insights to the concept of plant succession. Eventually, the British ecologist C. Elton in his book “Animal Ecology” (1927) laid the foundations for terrestrial animal ecology. There followed rapidly in the ensuing decades the development of quantitative community ecology as a field, and an appreciation of the dynamics of populations and of the relationships between populations in communities, the flow of energy and the movement of materials in communities (in the second half of the century), and finally the emergence of a science of systems ecology, in the development of which the American ecologists Eugene P. and Howard T. Odum played major roles.

Like all branches of science, ecology has become increasingly quantitative and theoretical, with an emphasis on mathematical modeling, population ecology, and feedback loops; scientists such as G. Evelyn Hutchinson and his student Robert MacArthur were important contributors in this area.

It needs to be emphasized at this point that ecology and environmentalism are by no means synonymous concepts: ecology is in fact a scientific discipline that deals with the relationships between organisms and with their environment and develops logical ways examining and making predictions concerning them. A concept such as “sustainable development” is necessarily based on the principles of ecology, as those principles operate in a social and economic context. Notwithstanding this fundamental distinction, the development of the field of ecology into a strong scientific discipline during the course of the twentieth century is one of the factors of fundamental importance allowing us to evaluate the dilemma that faces us as we enter the new millennium. The whole set of biological relationships that it comprises provide the basis for understanding the reactions of different sets of populations, whether of humans or of other kinds of organisms, to their changing environment. Ecology likewise, especially through the synthetic field of conservation biology, illuminates the fundamental principles on which our biological heritage can potentially be conserved for our future welfare.

Environmentalism in Twentieth-Century America

Environmentalism in the United Stateswas marked in the early years of the twentieth century by the emergence of the remarkable leadership of Gifford Pinchot, John Muir, and Theodore Roosevelt. These inspirational men considered in their individual ways that our natural resources should be managed so as to serve the needs of the future as well as those of the present: their influence was enormous, and persists to the present. They built particularly on the concept of parks and reserves, and that of safeguarding natural resources for all people. Among the events that marked the growth of environmentalism prior to World War II were the establishment of the National Audubon Society (1905), the controversy over Hetch Hetchy Valley in the Sierra Nevada of California (the valley was granted to San Francisco in 1913), the Migratory Bird Treaty Act established with Canada (1918), the establishment of the Civilian Conservation Corps (1933), and the passage of much Federal legislation to regulate forests, water, and soil erosion during the 1930s. The influence of cartoonist Ding Darling (1876-1962; Lendt, 1979), who published widely syndicated and much-appreciated environmental cartoons from 1916 onward, cannot be overestimated. As chief of the Biological Survey (later the Fish and Wildlife Service) in the 1930s, and because of his wide networking, he contributed a great deal to making Americans aware of their environment and what they were doing to it, and to the world – he clearly has an international vision of the environment, and projected that vision in many ways. And these are just a few samples of what was going on during those years.

During World War II, environmental concerns were largely sidetracked by the urgent ones associated with the war effort. Following the war, there occurred a period characterized by what Shabecoff (1993) called "careless optimism and materialism.". Environmental concern gradually returned, however, as people were confronted on all sides with widespread evidence of severe problems. During these years, events such as the severe air pollution that occurred in Donora, Pennsylvania, in 1948, in which 20 people died and 14,000 became ill; the London "Killer Smog" that left 4,000 people dead in 1952; and concern over soil loss, water pollution, and the destruction of natural resources drew widespread attention and lead to the enactment of new laws protecting people and natural lands.

One of the first books to call attention to these problems forcefully to a general audience was Fairfield Osborn's "Our Plundered Planet" (1948), which by its title as well as by its substance helped to stimulate serious and widespread debate. Osborn considered "the grand and ultimate illusion [to be] that man could provide a substitute for the elemental workings of nature". The concerns expressed by Osborn gradually moved to center stage in the public mind, his book having played a major role in stimulating concern about the environment and the directions in which we were heading.

Aldo Leopold, a great conservationist and philosopher, wrote some of the most stirring essays in the history of the field; his posthumously-published "A Sand County Almanac" (1949) has inspired generations of environmentalists. This book immediately became a landmark of the movement towards what we would now call sustainability, and is surely one of America's finest gifts to the world conservation movement, and thus to future generations. Leopold's "land ethic" speaks of a complex world dominated by human beings, who thus have either the power of good, nurturing care of their land, or the ability to degrade and destroy it. In his words, it "changes the role of *Homo sapiens* from conqueror of the land-community to plain member and citizen of it" (1943, p. 216).

Partly as a result of the writings of leaders such as Osborn and Leopold, and partly because of the increasing evidence of environmental degradation seen ever more widely, public concern over environmental matters reached new heights in the 1960s. The publication of "This is the American Earth," an exhibit-format book featuring the photographs of Ansel Adams and the poems of Nancy Newhall, by the Sierra Club in 1960, made a significant contribution to environmentalism and a new way of thinking about the Earth at a spiritual level at the start of the decade. Over the following years, many influential writers and speakers began to warn of the dangers of excessive human domination of the Earth, generalizing from when had earlier been seen as individual, unconnected problems. They did so during a half century in which a world population that had grown by 850 million people during the preceding 50 years to a record level of 2.5 billion continued to increase at accelerated rates to its present level of 6 billion people. Such growth, coupled with industrial expansion from 1945 onward and increasing expectations on the part of consumers, greatly increased the strains on all ecological systems in ways that had become widely evident by the 1950s and 1960s.

In 1962, the first excepts of Rachael Carson's "Silent Spring" appeared in The New Yorker, and our common vision of our relationships with our planet were permanently altered. Clearly the most important environmental book written in America, "Silent Spring" focuses on chemical pesticides, but with clear vision charts the destruction that technology can bring if carelessly applied. Carson presents a vision of a future world in which intelligent people can create a sustainable world. By doing so in such a convincing way, she moved environmentalism permanently to the center of the American agenda. Another landmark work was published near the end of the decade, when Paul Ehrlich's best-seller "The Population Bomb" (1968) dramatized and made available for a wide public for the first time the problems associated with rapid growth in human population, in effect adding a new dimension to the environmental debates.

The gathering momentum of the environmental movement culminated on Earth Day, April 22, 1970, when some 20 million Americans, one of every ten people in the nation, massed to demonstrate their concern over the state of the environment. Environmentalism had emerged as a mass social movement, resonating with civil rights and the other major social movements of the day. Many new environmental groups had been organized, and they were growing rapidly along with others that had been in existence earlier. Starting with the National Environmental Policy Act, signed into law on January 1, 1970, the concerns of those who were attempting to lay the foundations for a sustainable future were embodied in our laws, followed by the passage of the Clean Air Act. The Environmental Protection Agency was created at the end of the same year; the Clean Water Act in 1972. Of particular significance was the establishment of the Endangered Species Act in 1973: the world's most comprehensive legislation dealing with the conservation of biological diversity.

Earth Day in 1990 was even more significant in demonstrating the degree to which environmentalism had pervaded every aspect of American society, from corporations to consumer life styles, and become a force that could not again be disregarded in the formation of public policy. What it called into focus, however, was that even though the environmentalism that was so strongly expressed in the 1960s had resulted in the establishment of outstanding environmental legislation, these accomplishments were not enough. Human nature combined with a failure to appreciate the global environmental situation, based partly on wishful thinking – the desire to continue on with "business as usual" – has resulted in bizarre and distorted conclusions like those of Easterbrook (1995), or the ones found daily in much of the economic press. Taken at face value, the assertions presented in such works would lead one to believe either that world economics functions in a vacuum, or that the natural productivity of the Earth and its maintenance and healthy functioning is of no interest in calculating human futures. Evidently, relatively few people in positions of authority are willing to deal with the shock that comes when the global scale of these problems is recognized. Yet it is patently true that economic growth can be sustained over the long run only in the context of care for the environment.

Global Environmentalism

On a world scale, the formation of the United Nations in 1946 and the subsequent development of the organization gradually led to an increasing emphasis on problems associated with the environment. In 1968, the International Conference of Experts for Rational Use and Conservation of the Biosphere met in Paris under the auspices of UNESCO, and became the first major international meeting to examine human impacts on the environment. From this conference came the Man in the Biosphere (MAB) program, which specifically called for new ways of considering this relationship, and implementing improvements in it.

Four years later, in response to environmental problems in the Baltic region, the 1972 United Nations Conference on the Human Environment was convened in Stockholm. Here, the Canadian Maurice Strong began his brilliant international environmental career, and, when acting as the head of the secretariat, brought about a strong examination of the relationship between the environment and development that has dominated international considerations of this area ever since. Building in part on the concepts expressed by the microbiologist and conservationist Rene Dubos, the conference examined the conditions under which human beings could exist in harmony with the rest of nature. Dubos' famous admonition, "think globally, act locally," has greatly influenced environmentalists, and his role in developing the concepts examined at Stockholm was of seminal importance., At the conference itself, a memorable role was played by Indian Prime Minister Indira Gandhi, who stated, “The inherent conflict is not between conservation and development but between environment and the reckless exploitation of man and the earth in the name of efficiency”.

Among the products of the Stockholm conference was the formation of the Governing Council for Environmental Programs, a body that changed the following year (1973) into the United Nations Environment Program (UNEP), with its headquarters in Nairobi, Kenya. Its global orientation has served the world well during the 26 years of its existence, with many solid accomplishments to its credit. Nonetheless, its status as an agency supported by voluntary contributions has tended to marginalize some of its themes and the conclusions of its deliberations, and many believe that a more central role for the environment within the U.N. General Assembly would be an appropriate response to the world environmental situation as we prepare to enter the new millennium. The scope of the world’s problems does indeed seem to cry out for such a solution.

Another, and very different, event of key significance in the elaboration of the concept of sustainability was the publication by the Club of Rome of “The Limits to Growth” (Meadows *et al.*, 1972). The study this book reports uses comprehensive mathematical models to develop its conclusion that if present trends in world population continued, that the limits to growth on the planet would be reached within a hundred years; that the underlying conditions could be changed to establish a condition of ecological and economic stability that would last for the indefinite future; but that if the world’s people decided to change these conditions, that the sooner they began, the more effective their actions would be. The remarkable feature of this book was its presentation of a comprehensive global model in which the various environmental, social, and economic factors that affect the human future could be considered in context for the first time. Although the study was widely reviled, particularly in economic circles, for the details of its projections, the majesty of its vision is as impressive today as when it first appeared, and the kind of reasoning it made possible remains fundamentally important. No enduring vision of the world’s future can fail to take into account the effects of population growth, of affluence (consumption per person), or of the use of inappropriate technology, all of which need to be addressed in achieving global sustainability.

In practice, however, the appearance of the book set off a strong debate between the “cornucopians,” who believed that environmental threats are grossly exaggerated, and that we should continue on with business as usual, and those who hold that catastrophes of various kinds are either upon us or just around the comer. What is certain in this debate is that early and intelligent actions will be required if some of the directions we are pursuing are to be changed; and change them we certainly must.

In the preceding remarks, I have deliberately not emphasized the growth of the global environmental movement, which parallels in different ways and with various regional and national characteristics that of the American environmental movement. McCormick (1989) and others have done a good job of charting the growth of what has become the largest social movement in history. One need only consider words such as Chernobyl, Times Beach, Brent Spar, and the Rainbow Warrior to understand how the concepts of global environmentalism have pervaded our collective consciousness, and why. Certainly this movement, from the grassroots up through organizations, will have a major role to play in the organization of our responses to the problems that we so evidently confront as we enter the new millennium.

Sustainability

In the history of the environmental movement, “sustainability” is a recent concept that has proved powerful in describing the different factors that bear on our future. In 1987, the World Commission on Environment and Development published “Our Common Future,” a report on the global environment in a human context. This report, which was adopted by the U.N. General Assembly calls for sustainable development as “development which meets the needs of the present without compromising the ability of future generations to meet their own needs”. In other words, it combines the need to protect natural resources with the improvement of living standards: ecological systems and human systems working in harmony with one another. Pointing out that the problems of the environment in relation to human development are well known, the Commission called for urgent action to address these problems and to set the world on a sound course for the future. The Commission produced a brilliant and well-reasoned report, with strong recommendations in most fields affected by sustainable development. To some extent, its conclusions were built into the Declaration from the Rio de Janeiro meeting five years later, but the objectives it laid out so clearly are still to be fully met. Achieving economic growth while taking into sufficient account environmental and social realities is our common goal, but it is very difficult to achieve. Despite the strong emphasis given this area in the recommendations of the Earth Summit at Rio (Sitarz, 1993), relatively little progress has been made. Why has this been the case?

Twenty years after the Stockholm conference, it had become obvious that the state of the environment had deteriorated greatly from its 1972 condition. The authors of "Limits to Growth" (Meadows *et al.*, 1992, p. 2) wrote in their new analysis, "Beyond the Limits," "Human society has overshot its limits, for the same reasons that other overshoots occur. Changes are too fast. Signals are late, incomplete, distorted, ignored or denied. Momentum is great. Responses are slow... if a correction is not made, a collapse of some sort is not only possible but certain, and it could occur within the lifetimes of many who are alive today".

In that same year, 1992, and once again organized under the tireless and effective leadership of Maurice Strong, the 1992 World Conference on Environment and Development in Rio de Janeiro re-emphasized and expanded upon these themes, and led to the development of several important international treaties, including ones dealing with climate change and a second with the protection, sustainable use, and fair and equitable sharing of biological diversity. The Earth Summit was a success to some degree, with the vision articulated twenty years earlier at Stockholm now widely accepted, and the depth of the problems confronting humanity generally understood. In addition, the enhanced role of non-governmental organizations (NGOs) in the meeting was an important advance that suggests one of the fundamental ways in which change may occur in the future. In addition, the organization of the Business Council for Sustainable Development was another important theme of the meeting, and one that has grown subsequently. The replenishment of the Global Environment Facility (GEF; formed in 1991), a financial mechanism to help developing countries deal with global warming, biodiversity loss, the pollution of international waters, and depletion of the ozone layer, was one important step, and several groups established or given new mandates at the time of the Rio meeting are addressing problems of great importance. What the Earth Summit did bring into sharp focus, however, was the huge difference between the concerns of the governments of industrialized countries, a fifth of the world's population with a per capita income of more than $20,000 and a life expectancy of 75 years, with those of the developing countries, four-fifths of the world's people, with a per capita income of about $1,200 and a life expectancy of 63 years. Some 1.3 billion people live in acute poverty, with incomes of less than $1 per day, 840 million of them receiving less than 80 percent of the U.N.-recommended minimum caloric intake, and thus literally starving.

When it became definite that India would attain independence, a British journalist interviewing Gandhi asked whether India would now follow the British pattern of development. Gandhi replied “It took Britain half the resources of the planet to achieve this prosperity. How many planets will a country like India require?” More recently, Wackernagel and Rees (1995) and others have emphasized again that if everyone lived at the standard of industrialized countries, it would take two additional planets comparable to Earth to support them, three more if the population should double; and that if worldwide standards of living should double over the next 40 years, twelve additional “Earths”. Aspirations to such a standard of living are clearly unattainable, and yet advertising continually tells everyone that it is both appropriate and achievable. Even those who already live in rich countries continually strive to seek to improve their standards of living. The paradox presented by these relationships can be solved only by achieving a stable population, finding a sustainable level of consumption globally, accepting social justice as the norm for global development, and developing improved technologies and practices to make sustainable development possible.

We certainly understand better than ever the nature of the problems confronting us, but our willingness to deal with them, as we enter the new millennium, remains very limited, whether they be global warming, the destruction of forests, toxic pollution, the control of nuclear arms, or the destruction of the biological diversity on which we so confidently hope to base so much of our future prosperity. Seven years after the Earth Summit, industrialized nations have not funded the important recommendations of Agenda 21, the principal document that emerged from the meeting, and seem less interested in taking those recommendations seriously as time goes by. The lack of leadership by the United States, the world’s wealthiest nation, has meant that the aspirations and plans developed in Rio de Janeiro in 1992 have mostly not been realized. How then can *we* and those who come after us expect to enjoy the benefits of a peaceful, healthy, and prosperous world in the twenty-first century and beyond?

Our collective inability, or perhaps unwillingness, to deal with conditions in the poorer parts of the world, on the one had, and the consumption patterns and lifestyles in more affluent parts of the world, on the other, pose serious obstacles to the attainment of global sustainability. With four-fifths of the world’s people sharing the benefits of only 15 percent of the world’s economy and their countries home to less than a tenth of its scientists and engineers, it is clear that the global system will operate properly only if there are increasedfinancial contributions from the North. In most of the South, environments are deteriorating rapidly, and for large areas, the conditions in which people live are clearly unacceptable and unstable, often leading directly to. environmental degradation (Shabecoff, 1996). Perhaps, as Shabecoff outlined, *we* are on the verge of a new enlightenment about the environment, but there are *few* indications that this is in fact the case.

Even though future societies based on information seem to promise less environmental degradation, the world view that so many of us share seems an unsuitable one for building a sustainable world. As Kai Lee (1993, p. 200) puts it, "How much misery will it take to make a global norm of sustainability first visible, then credible, then feasible, then inevitable? We do not know. And we do not know if the lessons of environmental disaster can be learned in time to ward off still more suffering. However bleak that prospect, we in the rich nations must bear the certain knowledge that our societies are both historically responsible for many of the circumstances that imprison the poor and that we will on average fare much better than they. Against this background it is possible to see that sustainable development is not a goal, not a condition likely to be attained on earth, as we know it. Rather, it is more like freedom or justice, a direction in which we must strive, along which we search for a life good enough to warrant our comforts".

Biodiversity

The word "biodiversity," which was coined by Walter G. Rosen at the U.S. National Research Council in 1986, in connection with the organization of a National Forum on "BioDiversity" sponsored by the U.S. National Academy of Sciences and the Smithsonian Institution (Wilson, 1988). Although it was a contraction of the familiar phrase "biological diversity," the new term took an expanded meaning, and as Takacs (1996) points out, has become the rallying cry currently used by biologists and others to draw attention to the global ecological crisis broadly. At the 1986 conference, we were still largely dealing with a concept of "biological diversity" that tended to connote the army of species in the world, our knowledge of theta, and the degree to which they were threatened by extinction. In contrast, "biodiversity," includes not only the genetic variation of those species but also all of the ways in which they interact with one another in communities and ecosystems – the entire fabric of life on Earth. Viewed in this broader way, biodiversity becomes the stuff of sustainable development, our primary hope for sustainable management of the planet in the future, and, of course, the resource on which we hope to base the coming "age of biology" over the decades to come. In other words, a concept that started as "biological diversity," transformed into "biodiversity," has added to its original connotation of a set of individual organisms a much broader social meaning. In that sense, it approaches the meaning of earlier broad concepts such as "wildlife" or "nature".

It is notable that the formation of the Society of Conservation Biology occurred in – the same year (1986) as the original conference on biodiversity. Like the conference itself, the formation of the Society signaled the maturity of an interdisciplinary effort in which the strands had been coming together for a number of years. An increasing maturity, based to some extent on the concepts that had been presented so poetically and well by Aldo Leopold 40 years earlier (Takacs, 1996), had deepened and broadened the conservation movement and the ways in which we can aspire to nurture the land and its living creatures.

The immediate inspiration for the formation of the concept of biodiversity was the sense of loss presented so clearly by authors such as Paul and Anne Ehrlich and Norman Myers in the 1970s and 1980s. Arguments based on the economic value of individual species, which are unquestionable and need not be elaborated here; those based on the value of ecosystem services, which in turn depend on interactions between species; and fundamental moral and ethical values all play important roles in explaining the reasons for the loss of biodiversity, estimated to amount to two-thirds of the species on Earth by the end of the coming century (Pimm and Brooks, 1999). Without biodiversity, we cannot respond well to the challenges we face, including global climate change: how will we form the new productive and stable biological systems of the, future? A habitable planet requires the maintenance of the living systems that support all living things on Earth, including human beings.

Current extinction rates are several hundred times higher than those that have prevailed for tens of millions of years, and habitat destruction continues apace, so that extinction rates of 1,000 to 10,000 times those that existed in the past will wipe out species at a rate that has not prevailed since the end of the Cretaceous Period, some 65 million years ago – at just the time when humanity bases so much of its future hopes on its ability to use those species for human benefit. Furthermore, we have charted only a small fraction of the Earth's biodiversity, perhaps 1.6 million eukaryotic species even given a name of an estimated total number of perhaps 10 million, with next to nothing on a global scale really known about such critically important groups as bacteria, fungi, and many groups of marine organisms. What we are losing, we do not even know: and perhaps never will.

A View of the Future

Over the course of the twentieth century, it has become overwhelmingly apparent that humanity cannot expect a healthy, peaceful, and productive future – in other words, a sustainable one – if we continue to live off the Earth's capital, rather than its interest: natural productivity. A world in which people are using or wasting nearly half of the total terrestrial photosynthetic productivity, one in which more than half of the available fresh water is already appropriated for human use, one in which the characteristics of the atmosphere are being altered rapidly, and one in which the species on which we hope to base the construction of sustainable and productive systems at the level of individual species and that of communities are disappearing in huge numbers – such a world will not be able to continue with its profligacy much longer without severe crashes of major ecological and economic systems (Meadows *et al.*, 1992). Global security likewise depends ultimately on environmental sustainability rather than on the expenditure of a huge proportion of the world's economic output to fund armies for rich, industrialized nations and poor ones alike (Myers, 1995). Food security, health, social justice – all are dependent on rising above our parochial and perhaps ingrained views of how to live, and learning together how to manage our planetary home for our common benefit. Empowering women throughout the world, seeking means to raise their status, and alleviating their poverty – microcredit has proved an effective strategy in this important effort – constitute among the most important actions to be taken to achieve sustainable development Science and technology need to be fully applied in our striving toward global sustainability (Lee, 1993), but they alone will clearly not be enough. The new Social Contract for Science called for so forcefully by Lubchenco (1998), one in which scientists will address the most urgent needs of society; communicate their knowledge and understanding widely in order to inform society's decisions; and exercise good judgment, wisdom, and humility, constitutes a powerful call to action in a world that needs such action badly.

As the century comes to its end, it seems clear that the regulation of economic policy, with allowances for supporting the actions of the private sector, will have more impact on the environment than direct legislative initiatives. Conservative economists and radical environmentalists agree that the true value of the materials that we are using must become the basis of the sustainable commerce of the future, and that irrational taxes that drive unsustainable activities by mis-stating the value of their materials should be abandoned. Indeed, Myers and Kent (1998) have estimated that perverse subsidies leading to the destruction of natural resources worldwide amount to some $1.5 trillion annually, approximately twice as large as total global military spending, and larger than the economies of all nations on Earth except the five largest – recognizing the undesirable nature of these subsidies and eliminating them or changing them in ways that will contribute to the. sustainability of global ecosystems and resources would be one of the most important actions that humanity could take as we enter the new millennium. Perhaps the world's major corporations could in their own interest pursue an agenda in which the actual prices of resources were taken into account. In the many design and construction community, for example, architects and building scientists are just now starting to operate by the rules of such an agenda, conserving energy and using new life cycle analysis (LCA) software tools to evaluate the environmental costs, such as resource depletion, greenhous gas emissions, and energy consumption, of materials from "cradle to grave". Green consumerism is growing rapidly, with more than 31 million certified acres supplying "green" wood products in 1999. In addition, and of great importance, national and global systems of green accounting to reflect the full environmental costs of economic activities would help.

By pursuing strategies of the sort just reviewed, it might actually be possible to improve the potential condition of the world, and to counteract humanity's partly hard-wired tendency to behave as if we were still highly dispersed hunter-gatherers, rather than members of a rapidly growing human race comprising six billion people, some very rich, but many living in abject poverty. How could we build the political will to accomplish this? In view of the failure of the United States and other leading industrialized countries to address responsibly the agenda proposed at the Earth Summit in Rio de Janeiro in 1992, we cannot legitimately enter the new millennium with a sense of optimism. Despite this, we must be as effective as we can for the sake of those who will follow us, and we have significant choices to make that will clearly influence the shape of the world in the future, as analyzed effectively by Allen Hammond (1998).

Concretely, we could continue to strive to move sustainability closer to the center of the United Nations agenda, where it would be recognized as the most powerful factor in determining human futures. The United States could ratify the Convention on Biological Diversity, and all parties could refocus its activities on its three key objectives, which will help to conserve biodiversity and improve livelihoods, rather than allowing it to be consumed by questions of gene technology that have at best a marginal bearing on the survival of species around the world. The reform of the activities of the Convention, and their redirection towards appropriate objectives, would be a major step forward in the field of sustainable development. A global plan for the preservation of species, properly funded, would result in the greatest gift that, we could possibly give to our descendants.

On the other hand, it may be that the model of a world driven by nations and the kinds of international institutions that were established in the wake of World War 11 will not prove to be dominant in the future. On the one hand, there is growing evidence that enlightened corporations are increasingly realizing that understanding and working with the conditions of sustainable development is a necessary prerequisite for success in the corporate world of the future (Hawken, 1993). John Browne, CEO of BP, for example, has set the company on a course that will embrace alternative energy sources and energy conservation, reasoning that in the face of global warming, they must do this if they are to continue to be a profitable energy company in the future. How much more likely BP is to prosper than companies that ignore the conclusions about climate change that are so evident to the scientific community? Ray Anderson, chairman of Interface, an Atlanta-based carpet manufacturer, is likewise reorganizing his company's efforts around the conditions of the future, where sustainability will be a necessary condition of successful business, rather than those of the past. There are signs that the forestry and fisheries industries are starting to take sustainability seriously, and indications that consumers will increasingly demand appropriate certification for such products because of their concern for the environment. If corporations listen carefully to their stakeholders and take care to operate sustainably, they will affect the actions of governments and international agencies significantly and help to create conditions for their own prosperity, and for the world's sustainability. Frameworks such as that developed by The Natural Step, a Swedish organization that is having much influence throughout the industrialized world, will provide convenient blueprints to help guide us along the path of sustainability – but Kau Lee's

(1993) principle that sustainability can perhaps best be viewed as an ideal, like justice, should be kept carefully in mind as we travel in that direction.

The kinds of grassroots activities that are promoting sustainability on a local basis have become a powerful force throughout the world: perhaps they are fundamentally only a reemphasis of what has been traditional. Whether establishing local clinics and sustainable industries in the Biligiri Rangan Hills of south India, people-based ecotourism centers in native lands in Kenya, rebuilding a broken landscape at the Bookmark Biosphere Reserve in South Australia, learning how to ranch sustainable on the vast grasslands of the Malpai Borderlands of New Mexico and Arizona, or simply rooting out alien plants on Albany Hill in the San Francisco Bay Area, the people who are pursuing sustainability in a direct and personal way will hugely affect the shape of the world in the future. Outstanding books like those by Baskin (1997) and Daily (1997), explaining in detail how nature works and how we benefit from it in ways that most of us never consider will continue to play an important role in stimulating our desire to achieve sustainability. For example, watershed protection, the determination of local climates, and the protection of crops by birds and beneficial insects, including pollinators, that live in the ecosystems surrounding them are examples of ecosystem services – goods that nature provides without charge if we maintain sufficiently the integrity of the ecosystems that support them. In the light of this awareness, growing numbers of people will find ways to consume less energy, to recycle their materials, to participate in the political process, to promote the acceptance of international understanding as a prerequisite for sustainability, and to support others, individually or in organized groups, who are pursuing these objectives.

For the basic conditions of change must clearly come from within us. A small minority of Earth's residents cannot continue to consume such a large majority of Earth's potentially sustainable productivity. By doing so, they will untimely destabilize their own future, as well as the futures of all other people. Population, overconsumption (among others, Schor, 1998, offers a powerful analysis of overconsumption in America), and the use of appropriate technology must all be brought into the equation if our common objective is to achieve a sustainable world in the new millennium. As Paul Hawken (1993) has put it so well, we need completely new ways of thinking about our place on Earth and the ways in which we relate to the functioning of natural systems if we are to find a better way to live in harmony with nature. Nothing less than a new industrial revolution (Hawken, Lovins, and Lovins, 1999) and a new agriculture (Conway, 1997) are required to make possible the sustainable world of the future. The task is incredibly challenging, but it is nonetheless one that we much undertake if we responsibly understand the realities of our situation, and for the enduring good of those who come after us. It is also a fundamentally spiritual task. As Cronon (1955, p. 90) put it, "If wildness can stop being (just) out there and start being (also) in here, if it can start being as human as it is natural, then perhaps we can get on with the unending task of struggling to live rightly in the world – not just in, the garden, not just in the wilderness, but in the home that encompasses them both".

In the words of Gandhi, most appropriate as we chart our course for the new millennium, "The world provides enough to satisfy everyman's need, but not everyman's greed". These words illustrated why Wilson (1993) was able to conclude that humanity would be able to overcome its drive to environmental domination and self-propagation with reason – why, in short, we are not necessarily suicidal in our approach to the world. In the spirit of Gandhi, one of the greatest leaders of our century, let us take his thoughts to heart and find the new inspiration that we so badly need at this incredibly challenging time. Global arguments may have little impact on the behaviors of individuals unless they perceive the crisis as unbearably severe, something that impinges on people's lives in dramatic and frightening ways. By then it will be too late. Our ethics and our values must change, and they must change because we come to understand that by changing we will be happier people, guaranteeing a decent future for our children on a healthier planet in more vibrant democracy in better neighborhoods and communities.

Many of the world's life-support systems are deteriorating rapidly and visibly, and it is clear that in the future our planet will be less diverse, less resilient, and less interesting than it is now; in the face of these trends, the most important truth is that the actual dimensions of that world will depend on what we do with our many institutions, and with the spiritual dimensions of our own dedication. Clearly, the opportunities that are available to us now are very much greater than those contemplated with such joy by those who gathered in St. Louis in 1904, and the stakes are much higher.

LITERATURE CITED

Adams, A. and N. Newhall. 1960. *This is the American Earth*. Sierra Club Books, San Francisco

Andrews, R.N.L. 1999. *Managing the Environment, Managing Ourselves. A History of American Environmental Policy*. Yale University Press, New Haven and London

Baskin, Y. 1997. *The Work of Nature. How the Diversity of Life Sustains Us.* Island Press, Washington, D.C.

Carson, R. 1962. *Silent Spring.* Houghton Mifflin Company, Boston

Conway, G. 1997. *The Doubly Green Revolution. Food for All in the 21st Century.* Penguin Books, London

Cronon, W. (ed.). 1995. *Uncommon Ground. Toward Reinventing Nature.* W.W. Norton & Company, New York

Daily, G.C. (ed.). 1997. *Nature's Services. Societal Dependence on Natural Ecosystems.* Island Press, Washington, D.C.

Easterbrook, G. 1995. *A Moment on the Earth: The Coming Age of Environmental Optimism*. Penguin Books USA, Inc., New York

Ehrlich, P.R. 1968. *The Population Bomb.* Ballantine, New York

Elton, C. 1927. *Animal Ecology.* Sidgwick and Jackson, London

Gottlieb, R. 1993. *Forcing the Spring. The Transformation of the American Environmental Movement.* Island Press, Washington, D.C.

Grove, R.H. 1995. *Green Imperialism. Colonial Expansion, Tropical Island Edens and the Origins of Environmentalism, 1600-1860.* Cambridge University Press, Cambridge

Hammond, A. 1998. *Which World? Scenarios for the 21st Century*. Global Destinies, Regional Choices. Island Press, Washington, D.C.

Hawken, P. 1993. *The Ecology of Commerce.* HarperCollins Publishers, New York

Hawken, P., A. Lovins, and H. Lovins. 1999. *Natural Capitalism. Creating the Next Industrial Revolution*. Little, Brown, New York

Lee, K.N. 1993. *Compass and Gyroscope. Integrating Science and Politics for the Environment.* Island Press, Washington, D.C.

Lendt, D.L. 1979. *Ding. The Life of Jay Norwood Darling.* Iowa State University Press, Ames

Leopold, A. 1949. *A Sand County Almanac.* Oxford University Press, New York

Lubchenco, J. 1998. "Entering the century of the environment: A new social contract for science", *Science* 279: 491-497

McCormick, J. 1989. *Reclaiming Paradise.* Indiana University Press, Bloomington and Indianapolis

McIntosh, R.P. 1985. *The Background of Ecology. Concept and Theory.* Cambridge University Press, Cambridge

McKibben, W. 1989. *The End of Nature.* Random House, New York

Meadows, D.H., D.L. Meadows, and J. Randers. 1992. *Beyond the Limits.* Chelsea Green, Post Mills, VT

Meadows, D.H., D.L. Meadows, J. Randers, and W.W. Behrens 111. 1972. *The Limits to Growth*. Universe Books, New York

Myers, N. 1995. *Ultimate Security. The Environmental Basis of Political Stability*. W.W. Norton and Company, New York and London

Myers, N. with J.V. Kent. 1998. *Perverse Subsidies: Tax $s Undercutting Our Economies and Environments Alike*. International Institute for Sustainable Development, Winnipeg, Manitoba, Canada

Nash, R. 1982. *Wilderness and the American Mind*. 3rd. edn. Yale University Press, New Haven and London

Osborn, F. 1948. *Our Plundered Planet*. Little Brown, Boston

Pimm, S.L. and T.M. Brooks. 1999. "The sixth extinction: how large, how soon, and where?" in Raven, P.H. and T. Williams (eds.), *BioDiversity*. National Academy Press, Washington, D.C.

Shabecoff, P. 1993. *A Fierce Green Fire. The American Environmental Movement*. Hill and Wang, New York

Shabecoff, P. 1996. *A New Name for Peace. International Environmentalism, Sustainable Development, and Democracy*. University Press of New England, Hanover and London

Schor, J.B. 1998. *The Overspent American. Why We Want What We Don't Need*. HarperCollins Publishers, New York

Sitarz, D. (ed.) 1993. Agenda 21. *The Earth Summit Strategy to Save Our Planet*. EarthPress, Boulder, CO

Stegner, W. 1980. "Coda: Wilderness Letter," in *The Sound of Mountain Water*, pp. 147-8. University of Nebraska Press, Lincoln

Takacs, D. 1996. *The Idea of Biodiversity. Philosophies of Paradise*. The Johns Hopkins University Press, Baltimore and London

Turner, B.L., II. (ed.). 1990. *The Earth as Transformed by Human Action. Global and Regional Changes in the Biosphere over the Past 300 years*. Cambridge University Press, Cambridge

Wackernagel, M. and W. Rees. 1995. *Our Ecological Footprint: Reducing Human Impact on the Earth*. New Society Publishers, Gabriola Island, BC, Canada

Wilson, E.O. (ed.). 1988. *BioDiversity*. National Academy Press, Washington, D.C.

Wilson, E.O. 1993. "Is humanity suicidal?" in *The New York Times Magazine*, May 30, 1993, pp. 24-28

World Commission on Environment and Development. 1987. *Our Common Future*

Acknowledgments:
I wish to thank for useful discussions in connection with the preparation of this paper Robert Archibald, Gretchen C. Daily, Anne H. Ehrlich, Paul R. Ehrlich, Paul Faber, Kate Fish, Chris Hammer, Paul Hawken, Peter Jutro, Robert W. Kates, Jonathan Lash, Jane Lubchenco, Harold Mooney, Warren Muir, Norman Myers, Kerry ten Kate, George M. Woodwell.

CHOICE, RESPONSIBILITY, AND PROBLEMS OF POPULATION

BERNARDO COLOMBO

1. Looking into the Past

The further we strain our eyes into the remote past, the more uncertain becomes our assessment of the size of the world's population, whatever the efforts we make and the instruments we use in carrying out such an inquiry. It has been stated that the estimates made for the beginning of the Christian era might be wrong by a factor of two. The figures advanced by archaeologists and those quoted in the Bible from the census of King David are even more divergent. And the extreme conjectures made as to the number inhabitants of North America before 1492 are in a ratio of 1 to 12, and of 1 to 15 for the whole continent. In spite of such uncertainties, it can be plausibly stated that from the birth of Christ until the beginning of the eighteenth century the annual population growth may have been on average well below one per thousand. This means more than a thousand years were needed for the population to double. And if we go even further back in our attempt to quantify population dynamics in the past, to when subsistence slowly began to be achieved by agriculture instead of by simple hunting and gathering, we can assume that there was a much lower rate of population growth.

Overall in this picture we can recognise the domination of the force of mortality. The impact of mortality was twofold. There was the elimination of survivors and the strong limitations placed on the years spent by women during their reproductive age. Equally, there was the factor of prolonged breast-feeding which reduced the duration of the time periods open to conception. In order to resist such conditions, and in order to maintain the population at practically stationary levels, mankind was compelled for a long time to take full advantage of its reproductive potential. The maximum recorded level of fertility is that experienced by the Hutterites during the period 1921-1930, with an average of 10.9 children before menopause for a woman who married at twenty, and three less if she postponed marriage by five years. This result underlines the importance of marriage habits. What happened before the modern era coexisted with local and general oscillations in the size of populations. The study of certain regions clearly demonstrates the effects of mortality crises. To combat such crises recourse was made to changing marriage patterns and practices. This permitted the recovery of population levels and of related economic standards. Within marriage, unhindered procreation was the normal rule. As a result, a responsible choice about marriage could act as an efficient safety valve in the case of populations where marriage was not universal and took place rather late in life.

2. The Demographic Revolution

In modern times a turning point in population increase in what have since become the developed countries took place in the eighteenth century. This led slowly but steadily to a new equilibrium between births and deaths. The impact was to be observed first in the control of sickness and mortality, and then in the sphere of fertility. It is not particularly important to try here to clarify what was the most relevant factor in shaping the development of the death rate: the epidemiological component (after the ravages of plague in the seventeenth century this pestilence ceased to wreak havoc); the increase in the availability of food (potatoes and maize may be mentioned); or the innovations introduced by Jenner, and so forth. The result is what really matters to us, and more specifically a major increase in life expectancy and the fact that almost all women are reaching the age of fifty.

With regard to the decline in birth rate – the other phenomenon responsible for this demographic transition – it is to be observed that the research into this area has attributed this development to a series of historical factors: industrialisation, urbanisation, secularisation, schooling, and a number of others. However, each explanation which is cited comes up against exceptions which weaken its general explanatory value. Industrialisation first took place in a country – Great Britain – where the decrease in fertility started late in the day. The same happened in Germany, where, furthermore, for a long time there had been a strong tradition of compulsory schooling. And the first signs of a containment of births appeared in rural zones of France. Lastly, with regard to secularisation, what connection does it really have with the baby boom anyway? Whatever the causes, in this area, too, it is the results which really matter.

Having made these points, it is easy to understand why it is so difficult to transfer these very debatable interpretations of previous trends in developed countries to what has taken place recently in the rest of the world. This difficulty is compounded by the fact that what happens in the more disadvantaged regions depends largely on their exposure to external influences: the control of mortality is an example of this. Here again, let us pay attention to the results: these underline the very fast transition which is underway in the developing world and show an extreme accentuation of the consequences of a temporary imbalance between the components of growth. In the recent past in Kenya the rates of growth were around 4% per annum, which correspond to a doubling of the population in less than eighteen years. This happened due to a situation in which, while death rates declined much faster than had ever previously been the case, early and generalised marriage, together with high levels of marital fertility, continued to prevail at previous levels. A computation carried out by Ansley Coale – a U.S. demographer – twenty-five years ago helps to clarify what that means. Ansley calculated that, at a rate of increase of 2% per annum (the rate which obtained at that time), in 6,000 years the mass of the world population would reach the volume of a sphere expanding at the speed of light. It should be emphasised that the exceptional level cited for Kenya is inferior to that which, given present controls of sickness and mortality, and with full realisation of its reproductive potential, mankind could possibly obtain.

All this shows that, given the state of our present knowledge, only one conclusion is really possible: the new conditions of the domination of mortality in the long run require the need for a globally inescapable drastic containment of potential fertility – on average a little more than two births per woman. In other words, mankind has built a wall in front of it which blocks its path, and which at present appears insurmountable.

It should be underlined, at this point, that what happened in the developed regions with regard to the dynamics of fertility did not take place under any pressure from above. It occurred as a consequence of free and autonomous decisions, taken at the micro-level of families acting in a certain social, economic, cultural context. The same cannot be said for some countries which are in a state of development: the strenuous campaigns for sterilisation in the history of one specific country, and the persisting policy of the one-child family in another, are prominent examples of this. The same may be said of certain strong pressures applied by the outside world, and even by international organisations. It is clear that this impinges on fundamental human rights. And here we encounter the core of the problems of today and of tomorrow.

3. CHOICE AND RESPONSIBILITY

3.1 At the Micro-level

'All couples and individuals have the basic right to decide freely and responsibly the number and spacing of their children and to have the information, education and means to do so; the responsibility of couples and individuals in the exercise of this right takes into account the needs of their living and future children, and their responsibility towards the community'. So dictates the World Population Plan of Action approved in Bucharest in 1974. A richer text, in terms of the concerns of this contribution, was inserted in 1968 into the Pastoral Instruction 'Gaudium et Spes' issued by Vatican Council II. In this, among the values quoted for the guidance of sound personal decisions, spouses were invited to take into account their reciprocal personal good – something which emphasised the shared responsibility of the couple. The principle of freedom of choice for parents as opposed to external interference is thus certainly established. But at the same time it is stated that this fundamental right is linked to responsible choice, and not just to any kind of choice. Responsibility and freedom of choice are complex concepts which need to be examined in detail. I cannot be responsible unless I find myself in a context of freedom which even if limited allows me a real multiplicity of attainable alternatives. Responsible action implies reference to a value and to alternative options; to the knowledge of these latter and of the consequences of the choices which are thus taken; to the availability of suitable means by which to achieve the goal wished for, or which duty demands; to the ability to evaluate and grade alternatives, and to make rational decisions about them. Responsible choice, it is clear, requires personal education.

3.2 At the Level of Governance

But whose duty and task is it to ensure everybody can have desired and wanted children? Children, indeed, whom one might consciously decide not to have because of circumstances behind one's own control brought about by social injustice or other people's mistakes and misdeeds. The exercise of responsibility cannot be seen one-sidedly. Otherwise, the right to procreate responsibly, which is strictly linked to that of free marriage, would be practically ignored for those who live in poverty through no fault of their own. Here we encounter the function of government. In fact, a government has a duty, and therefore a right, to engage in initiatives to the best of its cognitive and organisational abilities, for the sake of the higher aims which guide its life.

But it is difficult to speak of interventions in matters relating to demographic policy which do not run the risk of causing more harm than they intend to cure if they are not supported by adequate social policies. Research into the best paths to be followed to ensure a reduction in fertility, while maintaining a variability between families which reflects the free choices taken by the persons concerned, remains incomplete. We have before us a current and shocking demonstration of the eternal problem of the search for a system of social organisation which conserves the ever fragile equilibrium between authority and the consensus of citizens. At the level of individuals, the achievement of a satisfactory solution seems to require the attainment of personal autonomy in conformity with the heteronomy of a social order which permits the maximum perfection of every individual's own being. Without this personal tension, no organisational solution suitable to man, which is carried through by the state, can stand on its own two feet. The same holds true if the present situation of several developed countries is considered. Here the level of fertility is so low that replacement is not achieved. In Italy various sample surveys taken in recent years by an organ of the National Research Council have consistently recorded an ideal number of two children per woman. For several years only two thirds of that level has been reached. In my opinion, this can be seen as an expression of a sort of social illness, which will eventually worsen the problems produced by a rapidly ageing population. Faced with this situation, we seem to need some kind of revolution which carries out a complete restructuring of society as a whole.

3.3 At the Level of Society

Individuals and families on one side, and government or any public authority on the other, are responsible for choices. But they do not operate in a vacuum – they take decisions within the context of society as a whole and its cultural background. To make this point clear, I would like to give an example. In certain populations there is a strong preference – whatever the reason may be for such a state of affairs – for the birth of a son rather than a daughter. Abnormally high ratios of males over females at birth are thereby consistently registered. Selective abortion is the main cause, and this is not something which is imposed by an authority. Similar results – and this is another example – were observed for two years in the sixties in a technologically advanced country. The reason, this time, was the belief that girls born in those years were liable to produce problems. As a consequence of such behaviour, a portion of males arriving at marriageable age were denied monogamous marriage.

In my opinion, something of the same kind can be seen in certain sad facts which are now before our eyes. Population movements, whether free or forced, have always been important in shaping the territorial distribution of the population. Among these are to be found interventions which have the character of 'ethnic cleansing', a policy which sometimes ends in genocide. Such actions may be guided and imposed from above, by people raising them as a flag to bolster their own prestige. But it would be difficult for them to become a mass phenomenon if they were not supported by the cultural background of society as a whole. In such choices there is, I am afraid, a shared responsibility on the part of governors and governed. The most striking development, in recent times, in the area of population movements, is the phenomenon of urbanisation, particularly in developing countries. Political leaders can partly be responsible for this development. The political power of urban concentrations is much higher than that of a dispersed rural population. Because of this fact, it is possible that such leaders provide differential advantages to people living in cities. The usual push and pull forces then become stronger and lead to the unfavourable displacement of people and economic development.

Those in political power and the man in the street come together in the adoption of a position of relative inertia in facing up to the problems of population. Slowly but inexorably these problems will manifest their strong impact on demographic structures and dynamics, and with a number of related consequences. But at a specific moment it is difficult to understand the relevance of these issues to today's isolated actions which become easily postponed.

4. LOOKING INTO THE FUTURE

In this paper attention has not been paid to the well-known extreme variety of demographic situations which are now to be found in different countries. In the same way I have not dwelt upon the enormous changes which have taken place in the composition and distribution of the population of the world and which will lead to the already mentioned differentials in the growth of the various regions. The purpose has been, rather, to illuminate a long-term horizon which involves the whole of mankind. We have seen that, while we have reached an unprecedented personal freedom of choice in birth regulation, at the same time we are about to experience severe and inescapable constraints.

The achievement of a stationary population level has its costs. There is the risk that reasons for tension could become institutionalised in the case of small families. Interpersonal relations could be impoverished, the dangers of generational conflicts increased, and psychological problems overcome only with difficulty. In general, the educational potentiality of the family could deteriorate. To this can be added the social marginalisation which could be suffered by the much wider band of ageing people. Life would be greyer. In this approaching reality, I see exacting problems emerging which involve the whole of humanity, which, to solve them, will not be able to place trust in science and technology alone. To come to terms with these new realities, man will have to draw upon all his most deeply hidden spiritual energies.

THE SEARCH FOR MAN

JULIÁN MARÍAS

I will be short, because we have little time. I am going to talk about the search for man. I think there is a now a tendency, maybe even a temptation, on the one hand to prefer primitivism to full forms of reality, and on the other to embrace what might be called the myth of time, the idea of a simple duration which explains everything irrespective of what actually happens during that time. There is also a tendency to reduce realities to their constituent elements.

Many people say that man is extremely old. We frequently hear or read about the hundreds of thousands of years of the existence of man. The general idea is that man is extremely old, but for 98% of this time it seems that nothing happened. There was no change. This 'mankind' was beneath the level of what we understand by man. I think the point is to give an account of ourselves, and the accepted idea is that this to be found by unearthing the remains of man, that is to say bones, just bones, but I think even an animal is a living being, is a pattern of life, is a repertory of vital actions, and not mere bones.

I am afraid it is difficult to explain the fact that mankind for an enormous period of time did not change, did not display the attributes we find in ourselves, and that then in a few thousands of years there was an enormous acceleration, and that this mankind created everything we have, everything by which we define ourselves.

I think this is very unlikely. It is difficult to accept this. I think that the continuity, the biological continuity between animal and man, is evident. Of course doctors are now making transplants from organs, from animal organs, and placing them in the human body. This shows not only that the primates, but all higher animals, are very close physically, biologically, to man, but I think man is something different: a human person is a reality which is extremely different from all other realities, because in the reality of man, of the person, there is embedded unreality.

All realities are real, are present, existing, but this is not true of man. Man lives in the future, is expectation, project, insecurity, something which does not exist, and this is surprising, a reality which is extremely different from all other realities. If you look for instance at the birth of a person, it is evident that what the child is comes from his parents and our ancestors, and from the elements of the world, of the cosmic world of course, but in the whole he is entirely different, irreducible not only to his parents but also to our ancestors and to the cosmic world and even to God, to whom he may say 'no'.

This is, therefore, an entirely different reality, and I think that if you consider the whole you find something absolutely different. There is a tendency to deny or to doubt the creation of mankind. This is a very thorny question which is very difficult. I am sure it is not easy to solve, because we do not have the Creator, we do not find him, He is not present, He is not available. There is something different here. The creation of mankind is a very problematic subject which we approach with difficulty. But the creation of each man is entirely different because of this characteristic of being irreducible. The person who is born, who shares this reality which is unknown in the rest of the world, this reality with unreality, which consists in unreality, is something entirely new, something which adds to the rest of the world, including his parents. This means that we cannot find the Creator, we have to look for Him or to infer Him, but the fact of creation is evident, absolutely evident, because we understand by creation the radical innovation of reality, the appearance of a reality which is entirely new, which cannot be denied by others. This is what we call reality.

It is a very interesting linguistic fact that in Spanish a child, a small child, is called *"una creatura"*, and that in Portuguese the term is *"una criança"*. That is to say that the child is understood as something which is a creation, a new creation irreducible to others, to anything.

We speak of evidence and there are two types of evidence. On the one hand, there is the evidence of things, the evidence of reality. On the other hand, there is the intellectual evidence. For instance, we have a rock. A rock is evident, and the geologist knows what it is, how this rock was produced, and this evidence is what makes science and philosophy. A man is also evident, but the point is that man now prefers theories to evidence, and if there is a theory which says that this cannot be so, the man of our time rejects evidence and sticks to theory.

For instance, man is free, man lives as though he were free. We know that we are free, we have to decide, we are necessarily free. We have to take decisions and make choices. Everybody judges men because they are free, because we live as though they were free, but if there is a theory which says that man is not free, most men now reject the evidence of freedom and stick to the theory that man is not free.

This is what I call the fragility of evidence, which is something very important. I think that often people hear or read something which is evident and accept this evidence and see things this way and after a while under the pressure of what is said, of what is accepted generally, of what is repeated by the media and so on, they lose the evidence they had at first, they reject it, and they return to the point of view held prior to the discovery of this evidence. I think this is extremely important.

Therefore I think we have to give an account of ourselves, to give an account of what we are, of what man is, the man that we know that we are. Many theories speak of the ‘missing link’, but there is no living missing link. In reality, in the real world, there is nothing which is not either man or non-man. There is nothing which raises doubts. We cannot point to any reality about which we are not sure. There is either man or non-man. It is unlikely that there were missing links, and none of them exist now or is real in our world. Therefore I think it is better to think of reality such as it is, such as we find it, with the attributes which we consider belong to man, to human life, and this is mostly unreality, anticipation, project. Man is not a present reality, he is mostly a future reality: of the future and uncertain. There is no certainty. The word ‘future’ is not exact because the future means what will be, and we do not know if something will be. It can be; we project it; we imagine it. The reality of man is highly imaginary.

I think that present theories of man involve the search for something which is not man, for something which is not what we call a person.

SCIENCE FACING THE CRISIS OF SENSE

FRANCIS JACQUES

I do not know precisely what you want to hear from philosophy on the eve of the plenary session. Yet, I have been invited to join your working group from this point of view. Thank you for welcoming me, a philosopher, amongst you eminent scientists. Now, philosophy might be expected

– To provide a link between science and humanism. And then, what kind of mediation?

– To take part in the heuristic debate in a different way, with the goal of introducing some variety. Then, I might ask, what sort of variety?

– And to put crucial issues into the wider context of the crisis of significance (or 'sense').

This is the first insight in my present approach. It presupposes that *there is* a genuine loss of sense. The same point is made by other thinkers: 'The extraordinary success of the systematic investigation of the universe thanks to the procedures of the positive sciences is on a par with scepticism or indifference to sense.'[1] 'It is as if our society had renounced, even in its educational instances, to make propositions as to what regards the order of sense'.[2]

It could very well be denied by many scientists that there is *any* crisis at all within the domain of science. If there is a crisis of the meaningful, or rather a crisis of sense, this phrase does not belong to scientific terminology but rather to cultural notions. The Holy Father speaks of a 'culture of death'. We are indeed witnessing the end of what marked the European

---

[1] G. Cottier, 'Médiations philosophiques dans les rapports entre la science et la foi', *Science et foi* (Desclée, 1982), p. 112 (my translation).

[2] J. Doré, 'La foi chrétienne dans la société d'aujourd'hui', *Une Parole pour la vie,* (Cerf, 1998), p. 197 (my translation).

landscape throughout the nineteenth century: man was to be the end of man, he had to acquire the necessary means for this aim, even at the ultimate risk of using himself for that very means. A concomitant crisis of the educational system has affected the transmission of the finalities of our society which are increasingly denied by the young. It concerns the aims and purposes required of man by man. The heart of the crisis is reached when the very notion of crisis becomes problematic.

What changes in the topography of modern rationality could account for the breaking of coaptation between faith, reason and life? This is a typical question for philosophy. As the philosopher's mediation has been requested, I will drop some hints and make some suggestions.

Granted that truth finally releases a sense of sense, yet, today, one can hardly challenge priority being given to the question of sense. It should be explicitely raised in matters of discursive strategy. As a subordinate – though no less fundamental – issue, I will formulate the question of how to define the critical thinking which can ground the space of sense. Afterwards, in a rather provocative way, I will deal with some logical consequences of critical realism for the place of science in order to facilitate the debate.

The answer will be elaborated in three stages: the identification of the specific activity of science in the reality of questioning; recognition of the external and internal limits of scientific problematicity; and its reintegration and reorganisation in the field of sense.

I. THE QUESTION OF SENSE

Roughly speaking, sense in the full-fledged connotations of the word has to be delineated from meaning from a logico-linguistic point of view. When we say: a sense of life and death, the question of sense, and when we analyse the different meanings to be ascribed to the word 'sense', we come across various denotations.

Sense or a *direction* from past to future. That of the proper way of life. To give sense to the scientific venture would be to assert that science knows where it is going, and this would be a utopia. *The* direction of life is something different: it concerns man in his integrality, in every dimension of his proper world.

Sense or an *aim*. If life has meaning, it progresses towards some good. If science has *a* sense, it must have one aim, at least the increase of objective knowledge. Now, the purposes of man no longer appear to him as being able to ensure his own human nature. High-technology achievements demand such large concentrations of men and such a precise division of labour that this entails the under-development of whole parts of humankind. The avowed aim and object of the medical sciences is to fight for good health against illness. But it also happens that they also involve man in manipulations and dispose of his right to live or to die. In most cases, but not in every case, the ends prove to be in full contradiction with themselves, at the very moment at which they seem to have been achieved.

Sense also reads as *intelligibility* as far as man is concerned. Man cannot live in an absurd world. Once more, science is endowed with significance in so far it gives access to some sort of intelligibility through the modelization of reality.

Lastly, sense means *hope*. The religious sense of faith is a way to anticipate what we hope, to speak a meaningful truth, a realized sense.

Every scientist who gives a predominant place to significance in his thought 'must be confronted with the task of examining, directly or indirectly, in constantly renewed form, the process and aim of science in the light of the question of sense'. By itself, science is not on its own able to provide complete answers to this question.

As a first approximation, the space of sense can be defined as a place for an open dialogue, that is, where the scientist, the philosopher and the theologian could recover complementary functions and agree on the course of scientific investigation, the identity of man, the religious quest for salvation, and philosophical mediation.

The Interrogative Approach

Now, if there is a quest for sense or significance, a second point can be made clear. Epistemologists and logicians, such as R. Gale, J. Hintikka, and more explicitly I. Lakatos,[3] have constucted an interrogative theory of scientific research with precise determinants and constraints on questions and answers. The questions must refer to observational and experimental data within the framework of a theoretical model; the answers must fit this theoretical form which is selected according to its capacity to solve 'problems' in the strict meaning of the word.

Science denies itself the right to come to conclusions in the matter of questions which, because of their own nature, are not 'objective' because

---

[3] I. Lakatos, *The Methodology of Scientific Research Programs* (Cambridge, 1978).

they relate to models of living. Science debars itself from the questions of sense and value, whereas life is led actually by sense and values. It informs our material and social environments, but has no power to tell us how we should handle our mastership over them. So far so good.

Scientific questioning – including the inventing and solving of problems – is *not* the only possibility (let us designate it as ‘problematicity’). It cannot be denied that there is also a philosophical questioning with its own types of questions: is there a difference between meaning and sense? Does sense exist at all? For whom does sense exist? And in addition, how should we characterize the different inquiries into sense: perhaps as informal, recurrent and radical questioning?

Theological questioning shows another structure. It does not exactly run from question to answer but from the appeal of God to the response of man. In the *Confessions* of Augustine we discover this shift from a philosophical to a theological questioning – mourning the death of a friend, he writes: *ego mihi factus eram magna quaestio*. New demands arise within new dynamics for posing questions – numbering among them not only the essence of the *ego* but also the status of time, the category of events in theological history and others...This new possibility can no longer be defined as ‘problematicity’ in the scientific manner nor as radical questioning in the philosophical style, but as the ‘elucidation of mystery’ (*mysterium fidei*). Faith should not be reducible to a system of beliefs in the private area.

Possibly we should add the literary or poetic questioning: take for instance Kafka’s inquest into guilt in totaliterian countries or the search for the sense of death by R.M. Rilke. Poets, scientists, theologians and philosophers have as many different ways of asking questions about one and the same abyss, and they have as many diverse relations to the unknown.

Let us sketch along these lines a philosophically minded research program. Systematic inquiry should be carried out in relation to the following questions:

> a) What are the main features of these modes of questioning and correspondingly what are the characteristics of the types of texts that give expression to them? Asking what happens in the universe when we suppose that its radius is tending towards zero, is not to be confused with an inquiry about the metaphysical outbreak of being or the supernatural creation of the world.[4]

---

[4] J. Earman, *Bangs, Crunches,Whimpers and Shrieks. Singularities and Acausalities in Relativistic Spacetimes* (Oxford University Press, 1995), p. 210.

The constraints of physics cannot bind the Creator. But precisely to the extent that a supernatural cause of the beginning of the universe does not have to answer to the constraints of nature, scientists *qua* scientists do not have the right to ignore it.

b) How to define the main categories numbering as orientations for these questionings. Theological categories like Creation, Revelation, Justification, Incarnation, Redemption...are not scientific categories like beginning, causality or evolution, even if they present an apparent synonymy.

c) As far as thinking is interrogating goes, what is the transcendental status of the competential modalities of thinking? We remember the famous questions of Kant: what can I know? What should I do? What may we hope (*was dürfen wir hoffen?*). They provide three autonomous fields of transcendental inquiry, not without cross-connections which have to be defined.

About Anthropology

Let us see some of the consequences of the very conception of anthropology. Part of the question of sense depends on man's identity. What is it to be a man? We should not give too ready an answer, still less an answer on a single mode of interrogation. One should so to say let the question formulate itself in accordance with the wide-ranging operating modes of human interrogativity in a harmonous culture.

The search for man is multidimensional. Of course it is not equivalent to determining man as an object: this is the *problem* of man. Scientific anthropology describes the objective characteristics of man as seen from his objective qualities, an animal able to stand up, to make and use tools, to bury the dead of his community. The result of evolutive hominisation.

– On the other hand man may be seen as a poetical enigma, with the typical variations and oscillations of meaning you can discover in the humanities, since Greek tragediis. For instance, Goethe's statement in *Faustus: ich bin der Geist der stets verneint*...So goes the *enigma* of man.

– Furthermore, man may be seen as a *radical question* for himself, as the ultimate foundation of the cultural signs of humanisation. How is man to understand his world as an object, and how is he to understand himself as a being able to engage in multiple questioning?

Confronted with an anxiety-inducing obligation to have to define, from the evolutive theory of the world, the vision he has of himself.

– Finally, man could be seen as a *mystery* to which Revelation alone can introduce us. Man cannot keep his self at a distance. He has to face things which are altogether disproportionate to himself. For him, living is being related to God, to others, to the created universe. These relations are constitutive of his being. In so far as mystery is a source of inspiration, it is illumininating intelligence striving to understand. Thus man's nature transcends consciousness, as well as the objective knowledge he can have of it. Something of what is at stake will manifest itself: the mystery of man, the very impossibility of man defining himself, since for an essential part he shares in God's want of definition. The most impregnable and inexpugnable depth of man's identity would be alienated if deprived of its relationship with God.

In short, there would exist philosophical and theological anthropologies together with a scientific anthropology. We should dare to say so in our days and keep on reminding ourselves of this fact.[5]

We are aware that latter-day scientific anthropology was born of the parting from the philosophical questioning of man's essential being 'considered as' a universalising totalitarian myth issuing from man's reason. It even came to identify man as a natural objet. Thus, it appears that 'dissolving' man – not constructing man – is the aim of scientific research in the social sciences.'[6] Several reductionist statements seem to point to the will to have done with man, reducing the mental to the brain, the ego to a series of disincarnate events and so on. In fact, it should be possible again to formulate a number of features brought to light by humanistic studies in accordance with philosophical anthropology (such as personal status, creative power, absolute desire, jubilation due to knowledge), or in accordance with Christian anthropology (such as the status of created being, the disposition to search for salvation or an incarnated being's estate). Is this to be wished for? It all depends upon the quality of the reformulation, which can never be incompatible with a shift in categorisation.

The very first shift actually appears in Gn 3, 7. In the narration of the Fall, the Seducer sounds a warning note: the fruit of the Tree of Life will

---

[5] F. Jacques, 'Apologétique et théologie fondamentale après Maurice Blondel. De la controverse au dialogue', *Philosophie et apologétique* (P. Capelle ed., Cerf, 1999), pp. 287 ss.

[6] C. Levi-Strauss, *La Pensée sauvage* (Plon, 1962).

turn to poison should man lay hands on it. Incertitude shatters the primeval world of trust; nature appears cruel and inhuman. In taking hold of the religious categorial competence and usurping the knowledge God had reserved to himself (not omniscience, the ability of telling right from wrong), man denied his condition of created being. His view of things altered. The retribution for it? A distortion of desire towards lust, the exploitation of man and the universe by sheer will-power and covetous desires. Such are at least the essence of the temptation and its consequence: the withdrawing of God who would henceforth hide his Face from man's knowledge. The story of the garden of Eden does not mention that desire for knowledge and power could have been justified if it had not turned into lust. P. Tillich is the most honest of all exegetes when he writes: 'One is given but little evidence of the relation of Adam to the fruit of the Tree of Life whose access he had obtained at first and seen denied afterwards; he may not enjoy eternity without God. Likewise one can infer by analogy that he cannot possess knowledge without God, either.'[7]

The Bible's narrative from Genesis, according to Biblical anthropology, and the myth of Protagoras, according to the philosophical anthropology of Plato, attest to the existence of levels in the ontological structure of man in multiple coordinates. Both texts agree on one point: man has kept on asking about his own self from the very beginning of his existence; man to himself, so intimate and also so mysterious, is not just a product of nature nor a promethean being, nor even a political animal.

II. THE 'INTER-COMPETENTIAL' DIALOGUE

As far as the practical consequences are concerned, it would be suitable, P. Germain suggested, to create a device to designate working points of agreement between us: the experts in this committee representative of 'spiritual, cultural, philosophical and religious values' (or 'thinking' as I suggested personally). The function of this suitable device being 'an open dialogue' between science in the positive and precise epistemological meaning of the word and the other modes of thinking and questioning. Division or 'schism among the minds' (Laurent Schwarz) is to be avoided. In a pluralistic society dialogue is possibly the only means of coexistence. But the purpose behind establishing an open dialogue which would preserve a cultural *equilibrium and balance* between the essential

---

[7] P. Tillich, *Existence and the Christ.*

prospects of the search for man, does not mean encountering no difficulties at all.

Briefly sketched: how should we conceive co-operation among the experts in the absence of any methodology towards a dynamic for such open dialogue between science, philosophy and religion? Let us notice that there is an added problem for the theology of dialogues which might be interconfessional or interreligious...I would like to argue in favour of this sort of dialogue which I would prefer to call inter-competential.

> – Now about its possibility. We have some knowledge of partial approximation of it. The consultative committees of bio-ethics usually organize debates and discussions in a rather informal way, a few other working groups do as well. Why not seize the opportunity? Even if we should not over-simplify our relation to the unknown especially in a period of crisis of meaning, and even if we should preserve internal limitations in such a critical period.
>
> – I come to the difficulties and dangers we would have to face. First, dialogue in the democratic and rigorous sense of the word tends to be confused with 'plain conversation', 'polemics', 'negotiation', 'contradictory discussion'. As yet, the notion has not been conceived as a definite heuristic way of thinking. Second, each form of questioning tries to re-categorize others in perfect good faith. Each tends to stand alone in front of the fundamentals. I do not believe any longer that one and the same man can be an expert or a good scholar in more than one speciality, but he can control and rectify the formulation other experts are forging for his own questions and answers.

Another point to be elaborated, concerning the nature of the correlations between modes of interrogation: are they of a contradictory, contrary, complementary, or even of a compatible nature? They depend upon ideas concerning the relationship beween hypothesis, observation, and theoretical modelization. Their explanations, even the bare facts, are what they are only in accordance with the kind of categorization provided by a culture and the way the latter interrogates the world. But what is most crucial is their transcendental articulation.

Man for science... He cannot stand outside his mind so as to get a view of things, man and the universe. Man is involved in questioning through research, in fundamentally categorizing again and again the various classes of facts, and as a result is involved in the building up of theories, doctrines, interpretative systems and ideologies, to go back to the epistemic distinctions of K. Popper. How is man to understand himself in his own multiple ways of thinking – that is the most fundamental question, *Die Hauptfrage*, Kant would have said.

Science and the Crisis of Sense

This question, after the questioning we have just outlined, requires a broad answer. It will not be impossible for science to face a crisis in sense if the scientists listen to experts of other modes of thinking and first of all recognize them at their face-value, and listen and work in committees like this one. The practice of thinking comes to the practice of different relations to the unknown in correlation with the main modes of questioning. At the risk of incurring a reproach of reiteration, I venture to repeat that scientific questioning speaks of our interest in positive knowledge because our survival is at stake; the questioning of poetics stems from a legitimate wish to express an enigmatic facticity, the richness and varieties of the 'humanities' using a literary langage as means of communication between persons; and the religious questioning originates from a desire to elucidate a mysterious donation; each with a different categorial orientation, each on a different level of organization.

In the eyes of mere ideology, all forms of relationship between humans appear to be reduced to a single pattern, all realities transformed into objects and all objects into pieces of apparatus. Science becomes a cause of rupture in civilization. Yet, at the synodal session which concluded on October 23th 1999, many bishops declared that the time for ideological struggle against modern culture – more particularly against those of its determinants called science and theology – is now superseded. Away with that endless pessimistic view on the relations of Christian faith to science! Enough of incommunication and the harmful hits at each other!

It should be made clear that scientific quest for truth exceeds the concern for technical applications, its epistemological autonomy prevents it from being subjugated by economic interests. Of course this fact does not render it able to respond to the question of significance. The location of science in human culture has to be re-assigned. Part of the problem depends on the very identification of reason. At this price, only, could some real work be carried out on the venture of science, and only as long as scientists are ready to admit that non-scientific questions can arise from other parts of the scenery.

Should we speak here of a scientific – that is operative, mathematico-experimental – kind of rationality? Or of a rightly orientated reason, the *recta ratio*, taken into account by the Pope in his latest encyclical, *Fides et Ratio* (nn. 50-52)? One cannot, he says, speak of human reasoning separately from the ill directed uses of reason. Man's reason has been 'damaged', yet it also has shown possibities toward rectification. The Christians least inclined to inform themselves of the Magisterial position on the subject should apply themselves to reading this text instead of speculating about science and philosophy. My personal position on the matter is to dismiss both parties – the scientific and the philosophical.

John Paul II devotes section 77 to 'the work of our critical reason in the light of faith'. This is theological reason. The message is clear enough: reason can be saved only by faith. Yet faith will never be man's province without reason. The contention is far from being ineluctable. Again, the issue is a matter of response to ultimate questions bearing upon sense, truth and being. At all events, we run into the danger of giving rise to a new idolatrous scientism in declining 'to recognize as valid, forms and knowledge different from those proper to the positive sciences, and driving back into the domain of pure imaginings the theological as well as the ethical aspects of religious knowledge' (n. 88). This is no appropriate time to choose stricture in the name of a restricted rationalism.

On Rationality

Josef Ratzinger remarks that it was Augustine who, without the slightest hesitation, assigned Christianity its place within the domain of philosophical rationality as well as natural theology. The synthesis of faith, reason and life used to be a driving power for the Christian penetration of the world. How is it that this is no longer operative to-day at a high speculative level?[8]

Since the rupture caused by Galileo Galilei, physical science has founded a mathematico-experimentally operating rationality that has led to a profound alteration of the very concept of nature. What has occurred has rendered us incapable of achieving an inkling – at the level of intellectual demands – of a direction that could be of any use to our present and most urgent needs, that is to say 'an ethics of universal peace, practical love towards our fellow-men and the necessary means to overstep the boundaries of practical interests'. In this regard the general theory of evolution, which defines itself as the royal road of biology and 'more and more as pri-

---

[8] J. Ratzinger, 'La foi chrétienne et la question de la vérité', Conference at the Sorbonne, 27 November 1999.

mary philosophy',[9] clearly fails to attempt to remodel the human ethos. Why? Because the ethos of evolution 'ineluctably finds its key-notion in the domain of selection, hence in the struggle for survival by means of successful adaptation, and also in the triumph of the fittest and finally the strongest'.

For the theologian, the status of reason appears to be definable only in reference to that of faith. The use of reason is prior to faith, but with the help of the categorial presupposition of Revelation it can lead to belief. Faith, therefore, is not just an assent of reason, it also brings into play some act of the will.[10] In that case the fullest practice of reason is brought about by reason and enlightened by faith.

In fact, natural reason has been a real problem to all theologians in the latter part of this century, just as it has been to all philosophers. Indeed the very model of an 'emancipated reason' through its bare 'natural light' has flatly failed. When considering reason it is not just the same thing whether one starts from action (like M. Blondel) or from the experience of interpersonal communion (like G. Marcel) or from an affective center of consciousness (as M. Heidegger did).

Philosophical inquiries distinguish several types of rationality. At the same time, positive or natural rights also proceed from a certain type of rationality: the *practical*, if not juridical. Reason, as the faculty of all principles, has no longer to assert itself as being freed from all options of belief. Thus, as regards *critical* reason, its prerequisite for any rational approach is a clear conciousness of the limit that this approach precisely presents in relation to the reality dealt with. As a rule, the philosopher's reason can be thought in *several* directions: the intuitive, dialectic, ontological, hermeneutic, transcendental, without excluding the Thomist model which will retain the value of a regulating concept.

John Paul II refrains from proclaiming neo-Thomism the perennial philosophy of the Catholic Church – on the contrary, he mentions many trends of thought that are more recent and have 'produced philosophical works of great influence and lasting value' (n. 59). *Fides et Ratio* pleads in favour of a philosophical reason that recognized its own capacity for contention against theology. Balthasar was himself convinced that there was no theology without philosophy. Our prevaling mode of thinking has raised faith and reason to a permanent constitutive tension that actuates or will actu-

---

[9] *Ibid*.

[10] Aquinas, ST IIa IIae q2 a. 1 et 2.

ate the vitality of both philosophy and theology. As a matter of fact, some works related to theological questioning also deal with philosophical issues such as the natural and spiritual worlds, creation, time and eternity, the person. The cognitive modes are clear. Yet, in the typological and epistemic areas not everybody can transgress the boundaries. They are endowed with categorial sense. On the plane of textual immanence there are no gaps so to say – the strictest boundaries concerning the interrogative modes having been delineated as early as their organizing planning out.

Here is an example. Two interrogative modes bring face to face *two readings* of the universe: one can be scientific as the universe is questioned from the view-point of evolution. The other one is religious as it is questioned from that of creation. Man being the only interrogator of his self and the world cannot but ask the question whether evolution, to which he is historically bound, *makes sense* or not. To put both categories together, the proceedings consist in interrogating evolution itself by asking about its sense or no-sense, relating to man within nature from a theological point of view.

Instead of affecting mutual ignorance, or promoting hierarchies in learning, a positive attitude would call for dialogue between partners as subjects facing each other, with a capacity to control any capture and to start its legitimitating process. Then each, from his own categorial viewpoint, would help his partner towards rectifying and renewing himself. Then a better knowledge of the rooting of mankind in cosmos would allow us to understand better the working of the Saviour of the world, and extend his intervention of the category of events in theological speculations: Christ's commitment to saving man enables us to anticipate a new world.

A fairly good convergence is promoted when starting from the viewpoint of the theological categories of Creation and Redemption. The proclamation of Christ's resurrection from the dead implies a specific *Weltanschauung* while it also gives sense and meaning to man's life. In point of fact, it is time for the theologian to take up an evolving vision of the universe under the action of Christ (*in quo omnia constant*).

III. How to Survive Science?

Science is more and more conceived as our best means (if not the only one) to survive. The question in J.J. Salomon's recent book asking 'how to survive science?' is ironical. It bears the stamp of marked ideology. In this respect, it is unfair, needlessly provocative and, undoubtedly, far from being well stated. What is the true situation? Science is not intrinsically dangerous nor are all its effects equally so. Some of them serve man fairly well, bringing hope and enlightenment – the hope of freeing man from diseases, debilating labour or climatic conditions; enlightenment, by providing a space for authentic research into the structure of matter, the cosmos and life. We may take as granted that it may be dangerous because of misdirected effects which escape control in advanced techniques, and in trespassing its own limits when attended by ideological distorsions or philosophical extrapolations.

> – Science and ideological distorsions. Science for man? To man, science is an occasion for temptation. The truth about science is that scientific activities cannot escape this temptation of power which runs deep in man. Science gives access to a power which it is hard to oppose. Now, power corrupts and absolute power entails absolute corruption. And indeed one must have a staunch heart to resist such temptation. Contemporary technology is a reducer and destroyer of the person. A reducer whenever it bridles the person's imprescriptible prerogatives, by way of detection by sound or photographs, or by censorial operation. A destroyer, also because of the very diversification of constraints and instruments of torture, or from the deterioration of the conscience and the will due to chemicals whose massive and insidious use has been prompted by the progress of pharmacology.
>
> – Science and philosophical extrapolation. One cannot underrate the critical potency of modern reason. Should science change its view objectively to ultimate philosophy, it would then turn into an extremely dangerous tool, since objectivization outside its proper order can be instrumental in the annhilation of the human in man. Such are the misdeeds of self – imprisonment deprived of mediation.
>
> – According to the theologian, the connexion between science and faith is to be logically derived from the theology of Creation incorporating the origin of evil. Nobody can analyze this connexion without submitting scientific activity, like any other human activity to ethical interrogation. It should be recalled that the limitations enforced upon man's condition by sin do affect all his activities.

Truly another danger threatens, which is more insidious because it is more *intrinsic*. Scientific acts and view-points, in so far as they are human, are bearers of limitation and damage: being objectifiers, they are by nature reducers of realities endowed with the status of objects. The sheer fact of giving an orientation to the scientific eye or act can, under some circumstances, be fraught with ethical consequences. Whether they are 'displaced' in themselves or by reason of their orientation is a point that remains open to discussion: the borderline is not easy to delineate as it is up to scientific theorizing to extend its relevant boundaries as far as possible.

A. Eddington intuitively felt that in the relationship of microphysics with cosmology there lay one of the keys to the scientific intelligibility of the universe. The confession of Creation refers to another mode of assent, tied up with a questioning regime different from the cosmologic pronouncement on initial singularity. Yet the standard model of cosmology speaks for an evolutionary view-point. There is no way to by-pass discussing the importance of the evolutionary theory or the exclusiveness of the positive method as a unique mode of rationality.

This new paradigm, hitherto reserved to the world of the living, is now extended to the whole cosmos. For the purpose of studying nature, the observation principles of quantum mechanics are used, inferring that the universe seems to be set in order to give birth to an observer within itself. The quasi-equality of the larger numbers derives from constants in natural philosophy (c, h, G, mp, H, po, Mu) characterizes a universe inhabited with observers, leastways not incompatible with scientific cosmology and anthropology. From now onwards, this 'anthropic principle',[11] as soon as it is given a finalizing interpretation, will play the role of a criterion between possible worlds. Here the question arises: are we entitled to go this far? Two courses lie open to us:

1) the metaphysical *a parte rei*. One regrets that philosophers are only too ready to renounce the ultimate issue, alleging the crisis of metaphysics (*FR*, n. 56). Then, and then only, the ultimate conclusion permits disclosure of sense *a parte rei*.[12] The anthropic principle alluded to above might well be utilized in its strong form at the borderline of cosmological and metaphysical questionings. But as its interpretation is tied to finality, the universe emerging out of primary undetermination gains access to awareness through the emergence of man at the final stage of human history. An access to attention to the point that this finalizing of interpretation turns it away from science and renews its links to a philosophy of nature and a nat-

---

[11] Cf. J. D. Barreau and F. Tippler, *The Anthropic Cosmological Principle* (Clarendon Press, Oxford, 1986), ch 7.

[12] G. Martelet, *Evolution et création, Sens ou non sens de l'homme dans la nature,* (Cerf, 1998).

ural theology.[13] While emphasizing intelligibility in the course of evolution, it is argued that its proper cause is the concern of intelligibility and refers to a superior principle of unity.

2) the transcendental way, *a parte hominis*. The Pope has vividly pleaded the cause of a reason that is not afraid of questioning itself (*FR*, n. 27). In *Fides et Ratio* the Pope again pleads forcefully for restoring to philosophy that place – both mediating and propaedeutical in character – that falls to it by right, so that it can cooperate in a regeneration of sense. The theology of creation is not supposed to determine the value of the constant of gravitation. Its critical function is relevant in the field of faith. Philosophy retains a critical function in the field of thought: to manage the articulation of the two orders of reality or discourse in their respective autonomy. Whether it is the hermeneutics or, as I prefer to say, the erotetics of interrogative structures,[14] a decisive margin of initiative is preserved. In front of a purely scientific modelization, e.g. the irruption of mankind within evolution, many views can indeed be supported – a creationist's, an emergentist's, a materialist's – which are not inevitably adequate.

Critical Realism

The only issue for science to face the crisis of sense should be a recognition of its own inner limits in the light of its external limits. Then a reintegration and a re-articulation are possible in the sphere of regenerated sense.

In the relationship of science and faith, when considering the scientific reading from a theological view-point, one can see a recapturing of one mode of interrogation by the other – this recapture being largely unilateral. Were it handled unwarily it could lead to *concordism* and constitute an unacceptable subversion. Concordism referred to by either party – in a fundamentalist sense by theology, in a positivist sense by science – brings about conflict. Man in our days is tempted to reduce himself to a natural being caught as he is in a world ruled by the dominion of death. But religious man shrinks from such limitations on behalf of the other aspects of human identity and rationality to which the scientific approach has not

---

[13] J. M. Maldamé, 'Evolution et création. La théorie de l'évolution: ses rapports avec la philosophie de la nature et la théologie de la création', *Revue thomiste* n° 4, 1996, 575-616.

[14] Entailing epistemological consequences on the very status of the synthetic theory of evolution: cf. J. Gayon, *Darwin et l'après Darwin: une histoire de l'hypothèse de sélection naturelle* (Paris, Kimé, 1992).

done justice. Inured to *ontological discordism* which concludes to the existence of realities of different orders, it has taken a double truth course. An *epistemological discordism* recognizing differences in textual types and interrogative modes, would be more appropriate, on the condition it finds its own transcendental articulation within interrogative thinking.

The possibility of a regeneration of sense once restored in its transcendentals, allows us to grasp more easily how watchful philosophical mediation operates. I can see here neither concordism nor ontological discordism, only an outline towards *articulation*. This is a renewed form of *critical realism*. Thus to bring heterogenous levels of thought together, negative rules should be stripulated, such as: no omitting of what is still missing; no trespassing on other people's spheres of competence; no affirmation containing incompatibility. I have privileged a transcendental approach in order to argue that my project was to lay a foundation for an *interrogative* theory in scientific research in order to invest science once again with cultural value and hence to establish it within the economy of sense.

According to the philosopher it is essential to replace scientific *research* in thinking. Philosophical mediation manages an interface where all the branches of learning are dynamically related. Concerning for instance, original sin, mediation is in search of an ultimate convergence. Operating as natural philosophy, it remains with it to question to what extension of sense biology or palaeontology have contributed in the constitution of a natural history of man. As religious philosophy, it behaves towards it as an attempt in the light of the Scriptures to discover the significance of man and evil. As theological philosophy, it keeps in view dogmatic contents and Magisterial teachings. The possibility of critical philosophy consists in operating the erotetico-hermeneutical articulation. It should take care not to give rise to any scientism by declining to admit the legitimacy of forms of knowledge different from those proper to positive sciences, throwing back to the realms of sheer fancy theological knowledge together with religious or ethical learnings (*FR*, n. 88).

A way could be opened which allows us to set scientific knowledge and Christian revelation in fair reciprocity. It is only a question of reaching a synthetic understanding of the reality of the world and the destiny of man's innermost self. Following such a course of thought, one endows the recognition of Christ as *Logos* with cosmic extension, in so far as he is the head and fulcrum of the renovated world. It follows that when connecting the theological considerations of man's place in the universe with the renewed version of the world and the emergence of life as imposed by space physics, cosmology and genetics at the turn of this century, one comes across the hope of an eschatological Coming. The present time would be ill-chosen indeed to weaken one and all of our fields of research in the name of a restrictive rationalism. Yes, there are many rationalities in the house of God.

THE FIGHT AGAINST DISEASES: COMMENTS RELATED TO “SCIENCE FOR MAN AND MAN FOR SCIENCE”

MICHAEL SELA

While the main topic of my presentation is science in search of solutions against diseases, therefore a topic definitely concerned with the contribution of “science for men”, I want to express my concern about the topic “man for science”. We cannot have only science applied to the betterment of mankind, or improvement of technologies: *There will be no applied science if there is no science to apply*.

We have to make science more attractive to young men and women at the start of their careers. We must fight more vigorously against the discrimination of women scientists – and I do not mean “affirmative action”. We do not have to lean backwards, just give them the chance they deserve. And we must include in our responsibility as scientists towards society at large the special responsibility towards younger scientists.

Responsibility towards younger scientists

It has been fashionable in recent years for scientists to dwell, both publicly and privately, on the complexity and ambiguity of their relationship with, and obligations towards, society as a whole. In the face of the extreme sensitivity we have all developed as a result, will it be seen as undue temerity on my part to suggest that perhaps there is yet another sphere of responsibility that has been overlooked: that is, the responsibility of scientists towards other scientists? Accountable to the world we certainly are, but what of our bounden duty to the young scientists in our midst, to those men and women whom we have undertaken – as their seniors – to guide, shape, teach and counsel? The fact, I believe, is that, trapped in the maze of scientific administration, puffing and blowing our way over the hurdles we confront in the increasingly competitive race for funding, preoccupied by the need to find solutions for problems such as space and equipment, submerged in the flood of printed and electronic information that inundates our desks, we are no longer as vigilant as we should be about guarding the beacon we have been charged to pass on to those who will follow us in the scientific hierarchy.

Perhaps, therefore, the time has come for us to return to more substantive attitudes towards our own profession. To remind ourselves – for our own sake as well as for that of those who model themselves on us – that science is more than merely one way of earning a living, and with it status. Let us face it: at its best, scientific research is not just another system locked into a larger set of systems. It is a calling. What is more, a calling whose success rests, in the final analysis, on the finest and the rarest attributes of civilized man: on intellectual courage, on hazardous hypotheses, and on the wisest uses of intuition. The responsibility of scientists to the society of which they are a part, and to which they contribute so significantly, is indeed an awesome matter, but should not overshadow other considerations. What has fallen by the wayside, I suspect, may be the responsibility of scientists towards their own tradition, towards the younger generation, and towards the flame itself.

Challenges in diseases

But let me now move to the main topic of my presentation – the fight against diseases. We have desperate situations in which present day science cannot even define the reason for a disease, as is the case for ALS – amyotrophic lateral sclerosis, also called in the States, Lou Gehrig's disease. And, on the other hand, the amazing finding that ulcer is a bacterial disease, caused by Helicobacter, and can be treated with antibiotics.

In neurological diseases there may be hope for nerve regeneration, and there are biochemical and genetic approaches to schizophrenia and paranoia. These will be the developments of the next century, but today the great challenges are Alzheimer and Parkinson, multiple sclerosis and myasthenia gravis. I cannot discuss here for lack of time vascular diseases, but I would like to devote the rest of my presentation to infectious diseases, autoimmune diseases and cancer.

Genetic and immunological diseases

The two important approaches are genetic and immunological. There are 30,000 rare genetic diseases such as cystic fibrosis, muscular distrophy or phenylketonuria. These are usually due to the defect in one gene, and there is a good chance of being able to correct it. But these 30,000 diseases form less than 1% of diseases, whereas 30 major diseases account for the other 99%. In the case of these diseases, both environment and genetics contribute, and the genetic moiety is multigenic and complicated. Nevertheless, a substantial effort is being devoted to elucidate the nature of such genes.

Concept of specificity

As far as immunology is concerned, I want to talk now about the notion of specificity in immune reactions, and their good use for therapeutic and prophylactic purposes. Vaccines are the method of choice to fight infectious diseases, and they are characteristically highly specific. This is due to the fact that substances used for vaccination are close molecular "cousins" of the virus or bacterial toxin that is the "troublemaker". Nobody expects one vaccine to be efficient for all infectious diseases. While the rate of success is great, we are still faced with those diseases which we are not yet able to prevent by vaccination, and I refer not only to AIDS, but to such old calamities as malaria and bilharzia. Actually, a new danger is tuberculosis: not only that classical tuberculosis is today the killer No. 1 of humanity, because the patients are not treated, but there is more and more of tuberculosis resistant to drugs and antibiotics, and the vaccination approach may be again cogent.

One new approach, possibly of great importance in the future, is DNA vaccination. Instead of immunizing with a protein – or with a mixture including the antigen of importance for vaccination – one isolates the natural DNA and uses it for immunization, with very encouraging results.

Autoimmune diseases

Now, a word about the concept of specificity and its extension to autoimmune diseases and to cancer. We are now extending this concept to autoimmune diseases and to cancer. Whenever it is possible to identify the putative cause of the disease, it should be possible to find a close molecular analog which will combat the disease. In one case of an autoimmune disease, that of multiple sclerosis, we have succeeded in developing a drug/vaccine which has by now been approved by the F.D.A. in the United States, as well as seventeen other countries.

This drug – or vaccine – as I prefer to call it – is a polymer composed of four kinds of amino acids, and prepared so as to resemble and cross-react immunologically with the main troublemaker of the myelin sheath of the brain, the myelin basic protein. This myelin basic protein can provoke an experimental disease – allergic encephalomyelitis, and our substance, denoted by us Copolymer 1, or Cop-1, can suppress the onset of the disease, and in rhesus monkeys and baboons, we showed that it can heal the actual disease. As this is an experimental model disease for multiple sclerosis, we moved to clinical trials. The phase 2 clinical trial was most successful. This was followed by several more big trials, before the FDA approved the drug/vaccine for daily injections for the exacerbating-remitting type of multiple sclerosis. We have proved recently that it can be given efficiently by oral route, and a trial involving 1400 participants is starting now in 9 countries. Copolymer 1 does not seem to have any effect on any other autoimmune disease.

In the same spirit we have approached another autoimmune neurological disease, myasthenia gravis, in which the disease is caused by an immunological attack on the acetylcholine receptor of our nerve cells. We are already successful in preparing a specific drug/vaccine against myasthenia gravis by limited amino acid substitution in two myasthenogenic peptides from the a-subunit of acetylcholine receptor. The analogs formed can heal the experimental myasthenia gravis in mice and rats, and we hope to start clinical trials next year. In principle, in every autoimmune disease in which you can put your finger on a potential candidate causing the disease, it should be possible to produce a close chemical relative that will suppress the disease.

Cancer

In the field of cancer there is an increasing number of tumor-specific or tumor-selective antigens, and therapeutic vaccination may soon become another weapon in the anti-cancer armamentarium, alongside surgery, radiotherapy, chemotherapy and non-specific immunotherapy. From recent reports it appears that even immunization against Alzheimer's disease is becoming a cogent possibility.

One hallmark of Alzheimer's is amyloid plaque, a protein deposit that builds up in the brains of those with the disease. In mice genetically engineered to develop an Alzheimer's-like condition, immunization with b-amyloid (Ab, the protein fragment that forms the plaque) reversed or prevented plaque formation and neural damage. The finding “raises the possibility that immunization with Ab may eventually be used as a treatment, or prophylactically, for Alzheimer’s disease”.

Globalization

For all these approaches to diseases, we must work together, as one world, globally. Globalization describes trends dramatically and relentlessly, increasing connections and communications among people, regardless of nationality and geography. But globalization without integration leads to a Babel tower. So to improve the health, and I mean first of all the developing world, we need both globalization and the integration of our efforts. And this must be done with great speed, as standing still is the fastest way of moving backwards in a world that is changing at an ever more rapid pace.

SOCIETY IN THE FACE OF SCIENTIFIC AND TECHNOLOGICAL DEVELOPMENT: RISK, DECISION, RESPONSIBILITY

ANDRÉ BLANC-LAPIERRE

The evolution of science and technology – and of their interactions with the general life of society – have accelerated tremendously over the past few decades.

Science has had a strong influence on the history of humanity: on the one hand, by clearing man's access to a better knowledge of the universe and improved understanding of its mechanisms, and on the other, by placing at his disposal the means which, by way of the development of techniques and technologies, have revolutionised living conditions.

The *growth in knowledge* is unequivocally a good thing which becomes part and parcel of cultural development. The same does not apply to the *usage of the means* generated by this knowledge. Humans can indeed use these for good, but also, unfortunately, for evil. Side by side with the immense *progress* achieved, for example, in systems of communications between people (in transport, telecommunications and so on), in agriculture, health, in the production of energy and materials, great harm on just as enormous a scale results from the increased efficiency of the means of destruction. The *risk of diverting knowledge and new technical prowess towards evil*, when they can be otherwise bring progress or are even primarily developed for such progress, undoubtedly exists. But there is more to this. *Any construction or accomplishment* (for example, large public works projects, means of communication, energy production developments, even medical operations and so on) *entails a risk*. *Any action entails a risk*. Taking the point to the extreme, *anything produced involves a risk* (it is the dose that makes the poison!). Man has been confronted with risks since time immemorial (floods, epidemics, earthquakes, wars and so on). However, with industrialisation and factors like the concern to take accidents at work into account or the development of insurance, and, moreover, with changed attitudes, today the notion of risk takes on an increasing importance in daily life, in everyday concerns and in the media, and, with the veiled disquiet induced by present day crises, society's very conception of danger is changing. True, there are indeed objective grounds for all this, but also showing through is a loss of confidence in the future. However, many signs should be leading us to look on this in a more optimistic light. To cite just one example, life expectancy which in part takes account, at the population scale, of the whole range of attacks to which it has been exposed, has risen spectacularly since the beginning of the century.[1] The corresponding epidemiological data are not well known to the public and there are many who believe that the general level of health has been adversely affected by repercussions from technological activities whereas in fact it has never been better. The overwhelming majority of harmful effects on health are, at least among the French, linked to behaviour (lifestyle, tobacco use and so on) and not to the environment in which they live. Here I quite happily quote Maurice Tubiana:

> All innovations, whether they concern technologies, food or products, and also behaviour and practices, are today subjected to constant criticism which weakens decision processes and destabilises the decision-making powers. What in this criticism are the relative weights of uncertainties and indisputable facts? Is it a consequence of a growing trepidation among people or does it result from the rise in power of a certain number of counterbalances? Does it stem from advances in prevention, which mean that the smallest anomalies are now detectable? Or, again, does it come from new principles for action elaborated in order better to preserve the living environment of future generations?[2]

For my part, I am convinced that the current feeling of disquiet, pessimism, and the malaise created by an emphasis on the immediate rather

---

[1] I refer to 'Risque et société', edited by M. Tubiana, C. Vrousos, C. Carde, and J. P. Pagès, *Symposium Risque et Société* (Nucléon, Paris, 1998). See p. 24:

Life expectancy at birth

1900		1980		1997	
M	F	M	F	M	F
44	45	70.2	78.4	74.2	82.1

[2] See (1) above and (2) M. Tubiana, *L'éducation et la vie* (Editions Odile Jacob, Paris, 1999).

than on the future, essentially results, for many of our contemporaries, from a loss of solid references such as religious, moral, family or national ones.

If we stick to everyday language, the notion of risk is quite simple. It bears on a potential danger, a potential peril, that could result from a given action envisaged that would or would not be given the go-ahead. To varying degrees, people will count on *beneficial* effects and fear *unfavourable* consequences. Put in this straightforward way, certain comments or questions arise.

Are the *benefits and risks clearly set out?* Has the presentation so expounded been arrived at through a process of *rational reflection* properly conducted and founded on *established experimental facts?* Or does it come from the attraction for *short-term gratification* without taking account of *medium – and long-term – consequences* (the pleasure of driving at high speed, drugs and so on)?

Is it a question of an *individual decision* within the reach of the individual or of a *collective decision* involving public powers (as in for instance the construction of large infrastructure projects, or health policy)? The probabilities brought into play will not be the same; I would even go so far as to say that, in the second case, on condition that certain thresholds are respected regarding the protection of individuals, the decision maker will work more on mathematical expectations focused on the community level rather than on individual probabilities. In the case of decisions that must be taken regarding projects affecting the community, it must be realised that, even if technical feasibility studies are conducted with the greatest care and lead to clear conclusions, there remains, for them to materialise, a stage which takes into account *economic* (cost, viability in competition with other projects and so on), *social* (such as people's wishes, acceptability by society), *political*, *moral* and other considerations. In this process, the roles of each actor – scientist, expert, politician and citizen – should be distinguished, although evidently one person may have more than one role. As Jean-Yves Le Déaut, Chairman of the Parliamentary Office of Assessment of Scientific and Technical Choices (France), has said, the politician's responsibility is a particular one: 'There is limited room for manœuvre: a policy of *prevention* (when the danger is known), even though necessary in the greatest number of departments, is neither possible nor sufficient. There are constraints that could hold a decision in abeyance: scientific knowledge on a subject evolves very rapidly; at the time when a decision must be made, this knowledge is not fixed. The time for action is short, with set limits; the time-scale for acquiring scientific knowledge is very long, expanded and “hard political decisions must be made on soft scientific certainties”.’[3]

It is in order to handle these uncertain situations that the precaution *principle* was developed. This appeared on the international scene at the moment when fears were first expressed about *climate changes caused by the greenhouse effect*. The Rio Declaration of 1992 stipulated: ‘If there is a risk of serious or irreversible harm, the absence of absolute scientific certainties must not be used as a pretext to postpone the adoption of effective measures aiming to prevent degradation of the environment.’ France is one of the few countries to have introduced this principle into its legislation. The Barnier Law of 2 February 1995 on the strengthening of environmental protection stipulates that ‘the absence of certainties, taking account of scientific and technical knowledge of the moment, must not hold back the adoption of specific measures, taken in proportion, aiming to prevent risk of serious *and* irreversible damage to the environment for an acceptable economic cost.’ There is a certain discrepancy here between the Rio Declaration which talked of serious or irreversible harm and the French law which says serious *and* irreversible. In addition, the Barnier Law states that the cost must be economically acceptable and recommends that the measures to be taken should be in proportion to the risk. Such proportionality would necessitate an assessment of the size of the risk and the cost of the measures.

These aspects could be discussed in order to gain a perception as to whether, given the scientific uncertainties that exist and the need for research and for additional observations, to which no definite lengths of time can be attributed, the precaution principle is a *legal* principle, an expression of *common sense* or a *rule of ethics*. It seems that depending on the classical approach founded on the link between scientific knowledge and action, the idea of precaution should, at Rio, have led to two decisions:

1. To extend to their maximum potential scientific studies on the relations between human activities (production of CO_2 and other greenhouse gases) and climatic modifications.

2. To study the means of production of sizeable quantities of energy without carbon dioxide emission and to encourage them.

In all cases, ‘zero risk’ does not exist, and one is still made to wonder if

---

[3] ‘Political Responsibility in the Face of Risk Management’, ‘La responsabilité politique face à la gestion des risques’, paper by Jean-Yves Le Déaut, symposium *Risque et Société*, mentioned in (1). See p. 264.

a risk is acceptable considering the anticipated *benefits*. But *what is meant by acceptable risk?*[4]

This is a complex question: a *government* that decides on large infrastructure projects (for energy, transport, civil engineering works and so on) is not in the same *position* as a *judge* who has the duty, some years later, of declaring a verdict on a question (a lawsuit or complaint before the courts) involving a development of that kind. Let us briefly analyse this point.

In the first case, the notion of *risk* is linked to the idea of *choice*. Before the final decision is taken, it is essential to define all options that could possibly be suitable. In a given situation, or confronted with a given problem, these are:

– To do nothing, let the situation 'rot' and take its natural course. Whether deliberate or the fruit of a certain unconscious passiveness, this attitude is indeed a choice in the sense that it will leave its mark for the future and there will be *consequences*.

– To weigh up several different solutions. Each will have its attendant *hope of benefits and fear of risks*. It makes no sense to fix attention only on the benefit and risk relative to just one of the possible solutions: they must be compared with benefits and risks associated with other solutions, not forgetting the one that entails doing nothing. Before proscribing a technology in order to eliminate the risks, the question must be asked if, by doing so, we are not condemned to accept another at least as dangerous, if not more so. For example, an unreasoned hostility to nuclear energy must not be allowed to obscure the fact that coal burning liberates carcinogenic products and intensifies the problem of carbon dioxide.

Risk-benefit analysis is made more difficult as the number of highly diverse factors increases: advances anticipated, people's safety, economic repercussions, acceptability among the populations concerned, and so on.

Moreover, it has to be noted that a quest for ever increasing *safety* in a given field in the end generates costs which rise extremely rapidly (safety has no price, but it has a cost!) and, beyond a certain degree of safety, it is reasonable to wonder if it would not be preferable to allocate additional sums to other needs of humanity, for example to other domains where safety is less well assured.

---

[4] On the notion of acceptable risk, here I am taking up again and adding to some ideas I aired during the 1996 Plenary Meeting of the Pontifical Academy of Sciences in a paper entitled: 'Science and Society – Reflections on the Evolution of their Interaction and on their Consequences for Culture and Education'.

A point which appears to me essential is that the choice made at the moment the decision is taken, even if it results from the then most objective and far-reaching study possible, will only prove itself to be a good one if the processes it sets in train are watched rigorously so that the conditions required for it to run smoothly are constantly met and the safety rules enacted are continually updated so that benefit can be gained from experience.

In the second case, involving the judge, the situation seems to be different because it does not entail comparison between several possible policies in order to choose one, which, rather, is the domain of the legislature and executive authorities. Instead, it involves saying if, in the actions carried out, the law has been complied with, the regulations observed, the official safety standards met, and whether or not the people involved have fulfilled the duties assigned to them among their responsibilities or could, instead, be guilty of professional misconduct.

In order to make a judgement on an action, it is absolutely essential *to base deliberations on scientific and technical knowledge as well as on the corresponding legislation in force at the moment of the action, not at the moment of judgement.* As for the issue of 'precaution and law of responsibility', I think it important to quote from a text by Marceau Long, Honorary Vice-President of the Conseil d'Etat, (which is taken up again in that Council's report of 1998): 'I am, for my part, sensitive to all that precaution brings to us. My personal conclusion is, however, that even if it is incorporated in the legislation, it is still only a political principle. Although precaution does not protect us completely from risks, it can sometimes allow us to escape from them, or much more often to avoid or soften their harmful consequences. We have to be careful not to derive from it too hastily the converse of the principle: if harm has been done, there has been a lack of precaution, and avoid making from this a foundation of responsibility.' It must not be allowed to happen that according to a notion of '*responsibility without fault*' someone might be responsible for what he *had to know*, which is quite usual, but also for what generally *had or should have been suspected.*

Let us come back to the *probabilistic* aspect of risk. In anything that is realised there exists a 'residual' risk 'due to chance' resulting generally from the chance succession of unfortunate events, each one haphazard in itself, none of which, most of the time, are particularly serious, but which, happening altogether, can lead to a disaster. It may be that if just one of these events were not to occur, that would be enough to preclude an accident. Quite astonishingly, *probabilistic risk analysis* was developed only in the early 1970s, with the report of N. Rasmussen, of the US Nuclear Regulatory

Commission. This report drew up the first general analysis of nuclear power stations. It examined a very broad spectrum of possible accidents, given the probabilities of occurrence of corresponding scenarios, and assessed the repercussions. Probabilistic methods have been applied in a great diversity of fields. They bring into play the systematic study of *fault trees*, *accident initiators*, *status graphs and so on*.

A certain reserve that could be termed 'popular' has emerged concerning probabilistic methods. This, generally speaking, results from two kinds of reasoning.

On the one hand, the notion of probability is not always well grasped. On tossing a coin, if we have found heads 100 times, we often think that tails will come up – and in doing so forget that, as Joseph Bertrand put it so well. more than 100 years ago, 'the coin has neither *memory nor conscience*'.

Another, deeper problem comes from the fact that the accidents that are considered correspond in general to very small risks: their *probability* is very small and the notion of *frequency*, much more meaningful than that of probability, is practically inaccessible on the scale of a human lifetime.

Among the specialists, much attention is given to the following point. Work is performed on *models*, for example models of existing nuclear power stations, whose operation and safety we want to monitor more effectively and improve, and for which we have feedback from experience, or models linked to 'virtual power stations' if there is a question of new installations being planned. Naturally, these models must be improved continually and it is, in particular, essential to make sure with the utmost care that one has not considered as independent certain faults which are in fact linked. The probability of finding oneself faced with the simultaneous faults of three *independent* organs each having a probability of 10-3 is 10-9. On the contrary, if these three faults are a *consequence of* each other, this probability stays at 10-3. This is the problem of the screening of all problems of common origin, associated with the breakdown of shared feed systems, or with a fire, and so on. At present, on passenger aircraft each hydraulic control system is installed in triplicate. It is clear that the considerable gain in safety resulting from this *redundancy* would be cancelled out if they had a common feed mechanism, the failure of which would paralyse the systems simultaneously.

What is the significance of the probability values that result from the probabilistic analysis? What, for example, is meant by saying that the probability of a total loss of control of an airliner is in the order of 10-9/hour? It must be realised that such figures are linked to the study of models, which makes them more of relative value, even if these models are, as it happens, improved unceasingly by feedback from experience. However, if, by using the same model, we gain a factor of 10, we can admit that the safety has by the same token increased by a factor of the same order. In this way, the analyses that entail the use of these methods are important as starting points for improvements in safety.

The various people involved in decisions regarding the problems already referred to are all, to a varying extent, confronted with the notion of *responsibility* in the broadest sense of the word, not only of *justification* if afterwards they are called to account in the courts, but also of *action* in the sense of an objective to achieve, of an advancement to promote, or of a *mission* to fulfil. The responsibility can take a variety of forms depending on the nature of the question it relates to: the *responsibility of the 'scientist'* if it is a question of declaring on the state of the science involved; *the responsibility of the technical expert* for equipment and installations; *the responsibility of the judge* who applies the law; *the responsibility of the politician* who has to govern while taking full account of several aspects such as budgetary, sociological and international situations; and, of course, *the moral responsibility* from which nobody can be exempt. Naturally, one and the same person may be vested with more than one of these responsibilities at once, to varying degrees. The need for the clarity of a situation and well-prepared decisions, however, calls for a precise unambiguous description of the mission assigned, in the name of the knowledge and skills, and in virtue of the mandate, through which each player expresses himself. If a politician calls on *the expertise of a scientist and a technical specialist*, the latter must brief him on the state of current scientific and technological knowledge, possibly on the uncertainty attached to this knowledge, and on studies that could reduce this, while holding back on any input related to his own philosophical, political or other points of view. Naturally, the person who has the duty to decide must combine the arguments advanced by the scientists and technical experts with input that bears on economic, political, social and other motivations. He takes the decision and is responsible for it. The part played by each actor is thus defined, transparency is possible, and, probably, the decision is made under favourable conditions, with the responsibilities of each of these 'agents' clearly marked out.

To finish, I would like to stress the role that the scientific community, the universities and the Academies of sciences should play, *without compromising on the fact that risks are real or that they should be assessed in a reasoned way*, in assuaging the excessive and often irrational fears currently expressed which, indeed, can paralyse any zest for research and enterprise. The role seems to me to be a dual one:

– on the one hand, *to enlighten public opinion* on the exact current state of up-to-date scientific knowledge available that is relevant to large projects underway by scrupulously distinguishing what science can and cannot say and by indicating what types of research could improve this knowledge. This contact with public opinion can pose problems for scientists because high levels of ability to explain and instruct are needed to find a common language, but it is essential to make the effort;

– on the other hand *active participation is needed in training young people, either directly or through their involvement in elaborating study programmes*. I believe that it is essential, in today's world, to develop experimental sciences to develop contact with real situations and, also, to cultivate a critical mind to enable people to sift and make proper sense of the enormous mass of information, truths and counter-truths which surge onto the scene.

I still believe that our young people are not put into contact early enough with the notion of *probability*, by which I mean the deep sense of what probabilities, statistics and related conceptions really are.

I have no doubt that if 'probabilist culture' was more widespread among the public and in the media, there would be less talk of the mysterious 'serial law'. This translates the idea that a catastrophe is not an isolated event in time. That could be described in considering the models that envisage the intervention of catastrophes occurring at random instances (Poisson) such that each of these instances would be associated with a cluster of concomitant catastrophes happening in a short period of time.

It appears to me highly important that students who do not intend to enter the scientific professions (aiming for fields like law, literature, the arts, medicine or the media) should receive the benefit of a good grounding in the processes and methods of science, incorporated into their courses, in the same way as they do for the development of their own culture. This does not mean going through in detail for them any particular chapter of science, but enabling them to capture the essence of scientific thought, of the way it has evolved, and its integration in the general body of knowledge.

Finally, in closing, I would like to stress one important point. That is, the weight which is attached to the problem of a rational assessment of risks in any action which is undertaken in the interest of ensuring a *development which is sustainable.*

CHALLENGES FOR AGRICULTURAL SCIENTISTS

TE-TZU CHANG

Historical Perspectives

Since the dawn of civilisation, advances in agriculture have played a pivotal role in allowing on-going progress in human well-being and human pursuits. Without a filled belly, no civilisation can flourish and achieve continued progress. Contributions by agricultural scientists have served to fuel dramatic advances in the supply of food, fibre and other basic necessities by applying Mendel's law of heredity, the combined use of water, fertilisers and pest control, and labour-saving machinery in large fields. The underlying knowledge for such scientific innovations has come from the natural sciences, especially biology, together with engineering, and the experience and initiatives of farmers themselves

Until recent decades, scientific innovations experienced widespread use in the developed nations but much less so in the developing countries. Meanwhile, total human population has risen from one billion at the beginning of the twentieth century to over six billion in late 1999. Of these about three billion have been added since the end of World War II. Food production remains inadequate in the developing world where a high proportion of the population remains under-nourished. The history of continued progress in agriculture has been the product of a true integration of technology, science and human endeavour. These processes have amply demonstrated the importance of the inter-dependence between scientific disciplines and demographic factors.

Achievements in the Developing World over the Last Three Decades

Since the early 1970s, giant strides in food production have been made in the developing world, in particular in rice and wheat, in what is widely known as the ‘Green Revolution’. Not only was the spectre of the predicted widespread food shortage of the 1970s averted, but calorie intake *per capita* has been appreciably raised.

Recent estimates calculate that about 78 percent of rice land has been planted with modern varieties; the corresponding figure for wheat is about 60%. In the year 1992-93, rice yield was nearly double that of 1961; for wheat, a gain of about 60% was achieved.

Yield increases in rice and wheat scored an annual growth rate of about two percent during the period of 1970-90, but the growth has slackened sime 1990 and the yield potential has remained the same since the late 1960s. Further advances in wheat and rice yields have also slowed down in recent years. During the same period, other cereals and root crops have also scored production increases but they have been less dramatic than is the case with rice and wheat. The massive US food aid programmes have disappeared.

The Human Factor

While the role of scientists has been emphasised up till now, we should not overlook the essential human attributes in these processes: dedication, pride, perseverance, and incentives. Agricultural research has been discouraged by the low respect and poor incentives accorded to its research, educational, and extension groups. Even more important is the less than equitable returns on the toil of farmer. Unless we attack the roots of the malaise, food insecurity will be the primary destabilising event on a grand scale during the twenty-first century. Its damaging consequences and ramifications will also affect the developed nations.

When scientists of all professions come to grip with the realities of the uncertain future with an eye on the plight of the under-privileged rural population, they will be in a better position to further the benefits of science and attract more young men to pursue scientific endeavour. Indeed, man and science are intertwined and are inseparable parts of scientific advance. Continuity is the essence of progress.

Rising Constraints in the Twenty-First Century

A number of wide-ranging and widespread constraints lie ahead. Productive land is on the decline due to competition from industrial and housing development, highway-building projects, and soil erosion. New irrigation projects have been installed with high costs and low local investment. Old projects are increasingly silted and in poor repair. Good quality water is becoming scarcer and more costly. Region-wide climatic aberrations have upset the stability of rainwater supply. Above all, the escalating rise in food production costs, poor returns from declining crop commodity prices, and the shortage of labour on farms, have all discouraged farmers from investing in increases in production. The dwindling supply of both natural and human resources has lowered the scale of vital improvements and on-farm experimentation. Most governments and urban communities are neglecting the primary food-producing sector. Meanwhile, the world's population continues to grow at burgeoning levels, although at a slightly lower rate than that envisaged by previous predictions.

Centres of modern and intensive production are beginning to face the aftermath of overly intensive cultivation: pest epidemics, soil degradation through erosion, salinisation and alkalisation, and the pollution of neighbouring areas.

What and how much Can Agricultural Scientists do?

While agricultural scientists will again bear the primary responsibility for dealing with a long list of daunting challenges, all sectors of society and the international community must mount an all-out and co-ordinated campaign to cope with the problem of food security on a global scale before serious food shortages suffered by an impoverished and populous planet grow into civil strife and international conflict. The basic element in enabling food supply to meet increased demands and expectations is of such paramount importance that it cannot be lightly treated as mere routine business. Research, educational and extension groups need to work together to sharpen their focus; and they should work together for a common cause. Agricultural scientists themselves need to re-assess their strength and weaknesses in order to redirect their strategy and logistics, and thereby recapture the momentum of the past decades. The necessary moves proposed are as follows: (1) a return to, and improvement of, the 'bread and butter' type of productive research which has suffered greatly from the heat waves of biotech; (2) an exploitation of the merits of biotech, but with due consideration of related issues such as ethics, intelligence property rights, bio-safety, and social justice; (3) more mission- and field-oriented-young researchers/workers, who need to be trained and supported. Above all, inter-disciplinary and institutional collaboration must be further strengthened and implemented. Agricultural scientists must respect and use the expertise, initiatives and experience of farmers and enrol the latter as partners in field research. Farmers are no longer an ignorant and passive sector. Enhanced education in rural areas will elevate their standing and representation in society.

Thus, the synergism of science and man can be reaped to mutual advantage. Such an interaction will enable us to deal with this urgent problem in time.

REFERENCE

Papers by T. T. Chang, P. Pinstrup-Andersen, and D. Byerlee *et al.*, in the 1999 P.A.S. Study-Week entitled “Food Needs of the Developing World in the Early 21st Century”, 27-30 January 1999, the Vatican.

THE MATHEMATISATION OF SCIENCE

LUIS A. CAFFARELLI

I was asked to make a short presentation on trends and directions in mathematics.

Mathematics has become a vast subject, with different techniques and scientific values. Even in a confined area like fluid dynamics, the same subject, say the Navier-Stokes equation, has a different connotation for different research groups (compressible versus incompressible, formation of singularities, zero viscosity limits, etc.)

I have chosen therefore to:

a) Stay very close to my area of expertise, non-linear analysis, partial differential equations and applied mathematics, where I could better present the issues.

b) More than a determined aspect or evolution of a theory, to discuss several examples of a trend that I feel will have enormous importance in my area of mathematics, as well as in our relation to the rest of the sciences.

The main theme of my examples will be that science and engineering are requiring the development of very sophisticated mathematical theories.

The enormous computational capabilities that are becoming available year after year have allowed scientists not only to look at more detailed models of existing physical phenomena, but also to be able to simulate complex materials and processes to optimize their design properties.

The first area I would like to discuss concerns mathematical development in image treatment (storage, enhancing, and compression). For simplicity, a black and white image simply means to provide a function (the grey scale) that may be piecewise smooth with sharp transitions, or dotted with very fine dots, or blurred and imprecise. Nevertheless, the eye has a special ability in grouping the essential features of it and reconstructing out of it a familiar image.

The first development that I would like to discuss is the theory of wavelets, which has to do with a way of extracting from a picture its detail up to a given level, and allowing us to reconstruct it (see Pictures 1, 2, and 3 Brushlets).

In trying to do so, there are two conflicting interests, very common in physics and mathematics sciences: size and oscillation, i.e. the choice between intensity and contrast.

Mathematically, this means having to choose between an approximation that averages in space, or one that averages in frequencies.

Averaging in space (a finite element discretization, for instance) will lose the detail in the oscillations; averaging in frequencies loses the local spatial detail. The representation of a function as a superposition of sines and cosines (the computation of the Fourier coefficients) depends globally on the function, although it attempts to represent it pointwise.

The compromise solution has been the development of wavelet theory. Wavelets are *bases* families of elementary profiles for decomposing function, intensity in our case, that are localized simultaneously in space and frequency.

In fact, they are *telescopic* both in space and frequencies, in the sense that they are:

a) Layered in space. There is a layer of size one, one of size 1/2, 1/4, 1/8, etc.

b) Layered in frequencies: they are mostly concentrated between frequencies 1 and 2, 2 and 4, 4 and 8, etc. (In fact they can all be constructed by translating and diadically shrinking a single profile, the wavelet) (Picture 4).

Wavelet theory has found deep applications not only in image compression but also in fluid dynamics, as well as classic harmonic analysis.

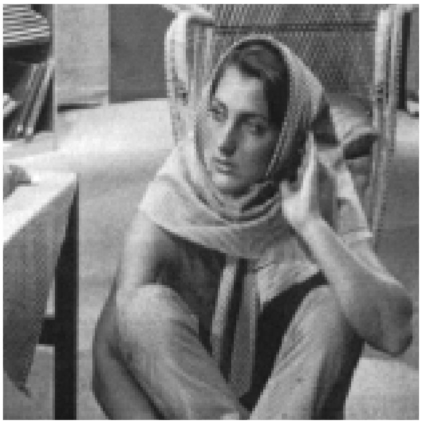
The other mathematical tool developed due to the needs of image treatment concerns geometric deformation and evolution.

In the same way that wavelets address an issue of multiple scales, geometric deformations address an issue of multiple models (Pictures 5 and 6: plane and geometric picture).

The issue is: given a blurred or a spotted, noisy image, how can it be grouped in order to make it a recognizable object. The idea, a classic one, borrowed from phase transition theory, is to assign to every configuration an energy that combines its closeness to the given, disorganized image and its degree of “organization”. (For instance, if it is a curve enveloping a region, its length.)

Next, one lets the configuration “flow” towards its energy minimum. For instance, a curve will evolve trying to minimize a combination of its

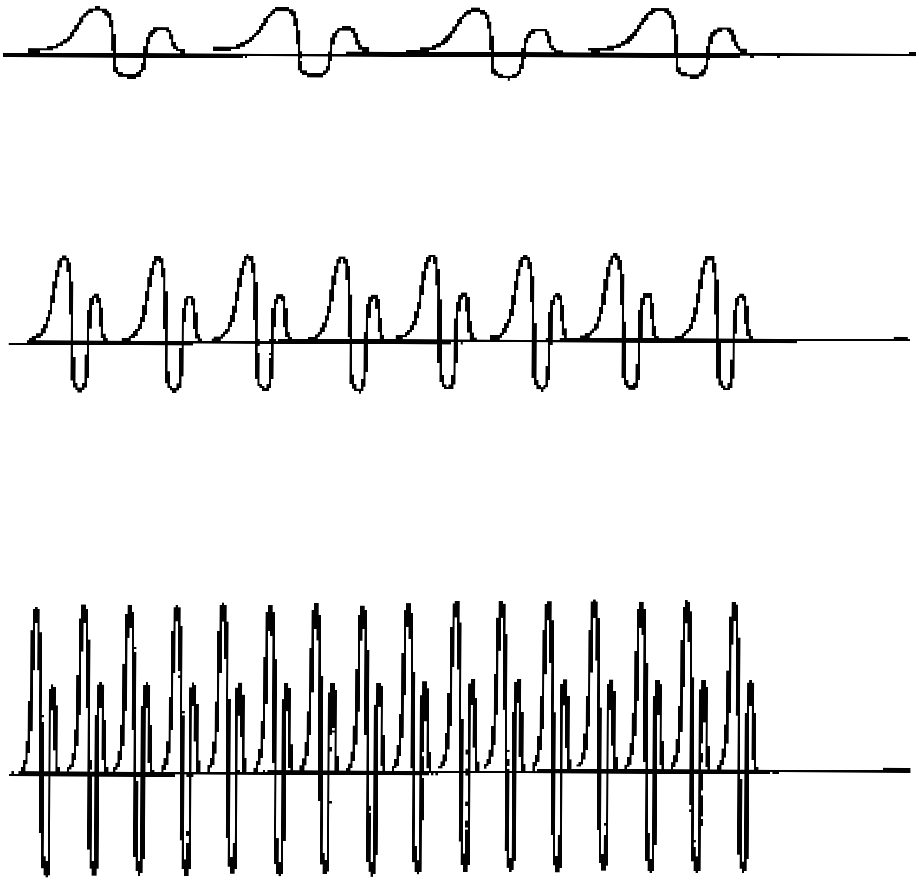
Picture 1 – 8:1 Compression



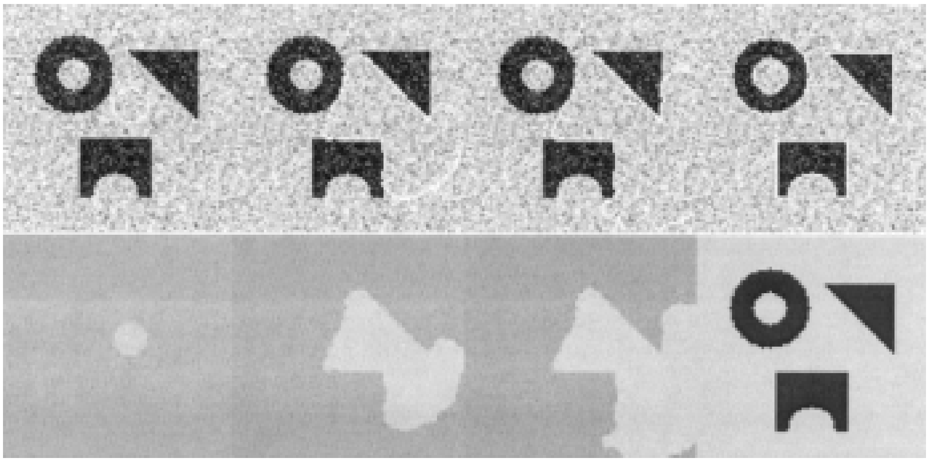
Picture 2 – 16:1 Compression

Picture 3 – 128:1 Compression

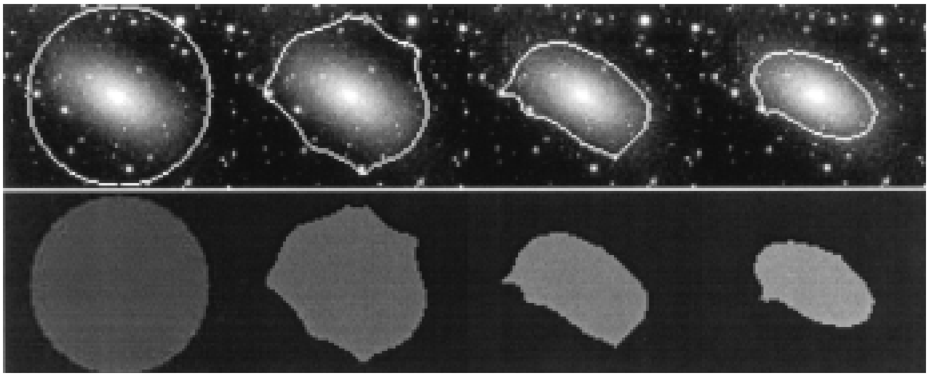
Pictures 1, 2, 3 – Brushlet Pictures. Yale Wavelet Computational Group.
http://www.math.yale.edu:80/YCM



Picture 4.



Picture 5 – Results for a very noisy image, with the initial curve not surrounding the objects. Top: u_0 and the contour. Bottom: the piece-wise constant approximation of u_0.



Picture 6 – An Active Contour Model without Edges

Pictures 5, 6 – Chan, Tony F. and Luminita A. Vese. "Active Contours without Edges." *IEEE Transactions on Image Processing.*

length and the intensity it encloses. When one tries to do that, singularities arise, and as the structure of the “approximate” configuration deteriorates, it is necessary to go to a higher model. For instance, a “field theory model” that adds “artificial viscosity” or diffusivity to the surface movement, to resolve the singularities.

For computational purposes we have thus a *multi-model* theory, where in areas of “normal” evolutions we use simpler geometric evolution, but couple them with higher complexity models to resolve singularities in the flow. The issue is, of course, when to use each model and how to couple them.

The issue of matching different models is a very important one; we will see another example later.

Next, there are two examples that come from continuous mechanics and one is multiscale, the other is multi-model.

The multi-scale concerns homogenization (see Pictures 7 and 8). Typical examples of homogenization are composite materials, or flows through layered rock formations.

Fluid or gas through a porous media, for instance, can be studied at several scales: at a few centimeters scale, the structure of the pore and the capillary properties of the fluid enter into consideration. At a few meters important factors are soil layers, large cracks, etc.

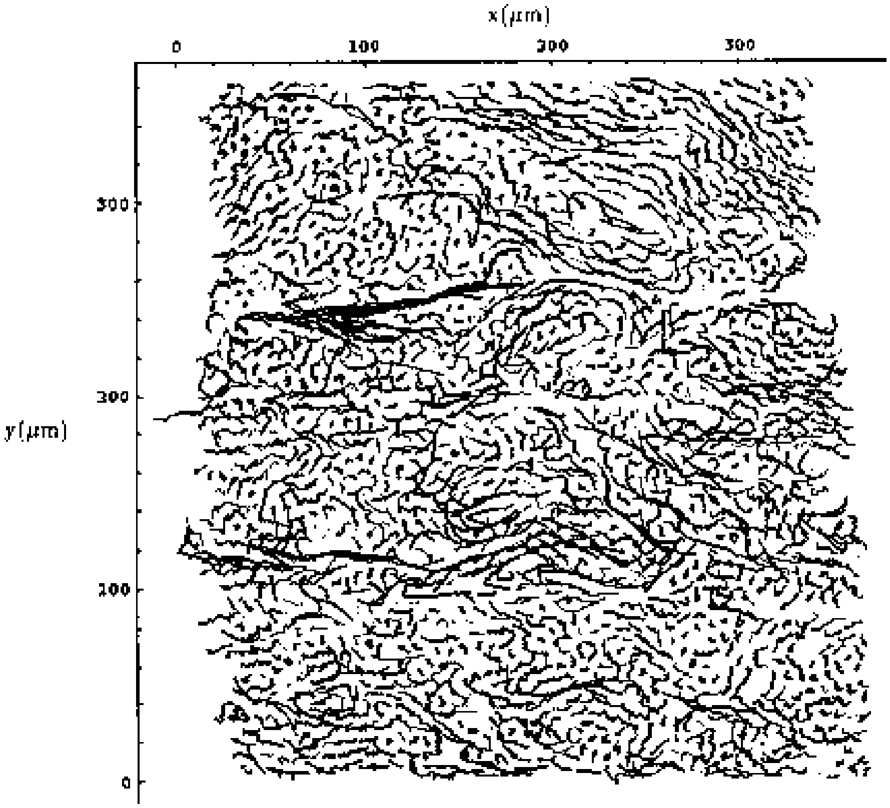
The interest, though, centers mainly on trying to simulate reservoirs at kilometer scales.

One must, therefore, model the interplay of each of the scales. At a kilometer scale, for instance, flow laws are much simpler, but the parameters (effective constants) or the non-linearities in these laws depend heavily on the small-scale behavior. Homogenization appears in many areas: elasticity, crack propagation, etc; and involves very sophisticated tools of non-linear analysis and probability theory.

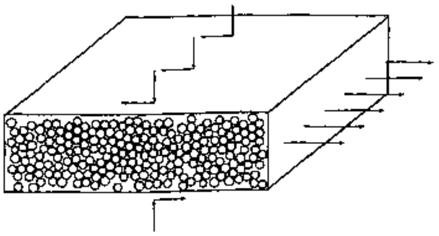
The last example comes independently both from aerospace engineering and semiconductor design. In terms of aerospace engineering, a typical example of the problem can be described as follows: a jet fired in an atmosphere of very low density goes from a very compressed regime to a very low density one in a length of a few meters.

According to its local density or density gradient there are several classical models of gas dynamics.

The continuous model, where densities are relatively high and shocks are weak, assumes that the gas moves locally in a coherent fashion, that is, there is locally a bulk velocity, one of our unknowns responsible for the flow.



Picture 7 – The centers of the 2000 fibers in 15 crossections 50 μm apart. All these centers are depicted in the figure which shows the movement of the fibers in the z-direction.



Picture 8 – Model problem for a unidirectional composite.

Pictures 7, 8 – Babuska, Ivo, Borje Andersson, Paul J. Smith, and Klas Levin. "Damage analysis of fiber composites." *Computer methods in applied mechanics and engineering.* 172 (1999) 27-77.

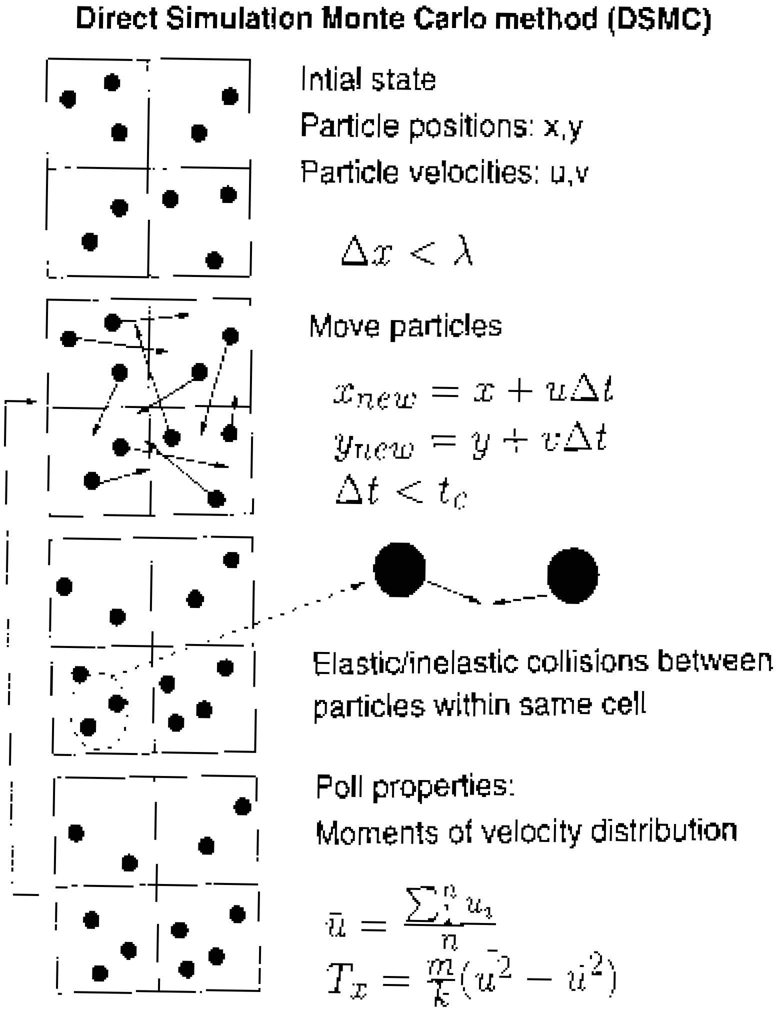
For lower densities, when particles spend a non-negligible time traveling before hitting each other, there are transport models where at each point in space there is a density of particles having a given velocity vector (so now, your ambient space is position and velocity) and colliding laws are prescribed.

Finally, there is always a basic computational model, called the Montecarlo simulation: just give a bunch of particles, with initial position and velocity, prescribe a "bouncing" law and see how they evolve by following each one of them (Picture 9).

This is, of course, the closest model to the "truth", but computationally very restrictive, so the issue is to use it only in those regimes where previous approximations fail.

How to match these three models is a central issue in continuum mechanics, since obviously the Montecarlo method is a simple fundamental way of modeling from granular dynamics to charged particle flows in semiconductor devices, but one would like to (correctly) transform it into transport or continuum approximations whenever possible.

The mathematical issue is, then, as density increases, what is the simplest proper transport model corresponding to a "bouncing" law, and further for higher local densities, the simplest proper continuum (hydrodynamic) model corresponding to the transport one. And, of course, how to couple different regimes (Pictures 9, 10, and 11, see p. I).



Pictures 9, 10, 11 – Roveda, Roberto, David B. Goldstein, and Philip L. Varghese. “A combined Discrete Velocity/Particle Based Numerical Approach for Continuum/Rarefied Flows.” AIAA Paper 97-1006, Reno, NV, January 1997, (see p. I).

Part II

SCIENCE AND THE FUTURE OF MANKIND

LIGHT AND MATTER

CLAUDE COHEN-TANNOUDJI

1. INTRODUCTION

Light has always been a fascinating subject for physicists as well as for scientists in general. What is the nature of light? How is it produced? How does it interact with matter? Is it possible to control these interactions? These are a few examples of problems which have always attracted a great deal of attention and which have been at the origin of important advances in our scientific understanding of natural phenomena.

The purpose of this lecture is to briefly review the evolution of our ideas on light and matter and to describe recent developments where light is used as a tool for acting on atoms and for cooling them at very low temperatures, in the microkelvin and even in the nanokelvin range. We will also mention a few possible applications of such ultracold atoms.

We begin (§2) with a brief review of the modern description of light and atoms and of the basic interaction processes between these two systems. We then show in §3 how it is possible to use the recoil of an atom absorbing or emitting light for controlling its velocity and for reducing the temperature of an ensemble of atoms, a method which is now called “laser cooling”. We finally describe in §4 a few applications of ultracold atoms to various research fields, like atomic clocks, atom interferometry and Bose-Einstein condensation.

It is impossible here to give an exhaustive bibliography on this research field. For further information, however, three references are given at the end of this paper, which may interest the reader. These are in fact the three 1997 Nobel lectures in Physics.

2. EVOLUTION OF OUR IDEAS ON LIGHT AND ATOMS

2.1 *Light*

Light was for centuries successively considered as a stream of tiny particles or as a wave. Now, we know that light is both an ensemble of particles and a wave.

First of all, light is an electromagnetic wave, consisting of an electric field and a magnetic field oscillating at a frequency ν and propagating in vacuum at a considerable speed $c = 3 \times 10^8$ m/s. Like any other wave, light gives rise to interference phenomena. If one superposes two separate waves with equal amplitudes, in some points, they vibrate in phase meaning constructive interference whereas, in some other points, they vibrate in opposite phase meaning destructive interference. This gives rise on a screen to a succession of bright and dark areas also called “interference fringes”.

The colour of the light depends on its frequency ν. The frequency spectrum of electromagnetic waves extends from radio-frequency waves to X and gamma rays. Visible light only covers a very small part of this spectral field. It is possible to analyse the spectral content of a light beam by using so called dispersive instruments subjecting light rays to a frequency dependent deviation. For example, if one directs a ray of sunlight through a prism, its frequency components are deviated in different ways. They spread out into different colours displaying what is called “a spectrum”.

At the beginning of this century, after Planck and Einstein’s work, it was agreed that light was not only a wave but also an assembly of particles called “photons”. More precisely, a light-wave with frequency ν is associated with particles, photons, with energy $E = h\nu$ proportional to ν and with momentum $p = h\nu/c$ also proportional to ν. In these equations, c is the speed of light, ν is the frequency of light and h a constant introduced in physics by Planck just a hundred years ago.

The main idea that emerged during the last century is the“ wave-particle duality”. The physical phenomena being observed cannot be understood by considering only the wave nature or the particle nature of light. These two aspects of light are essential and inseparable.

2.2 *Atoms*

Atoms are planetary systems identical to the solar system. They consist of positively charged particles, “electrons”, with a small mass, orbit-

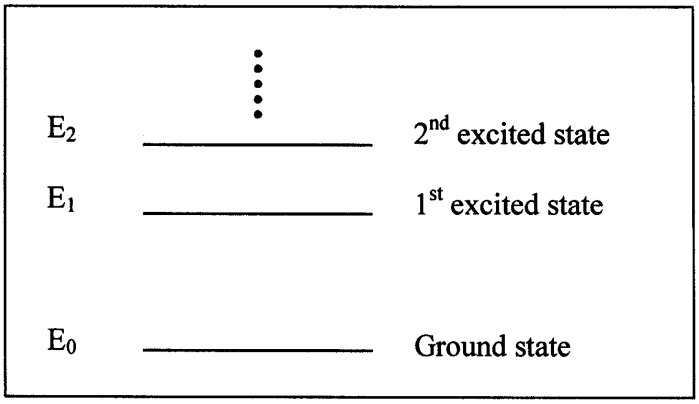


Figure 1: Energy levels of an atom. Each horizontal line has an altitude proportional to the energy of the corresponding level.

ing round a positively charged particle with a higher mass, called the "nucleus".

Physicists soon realized that classical mechanics was not appropriate for understanding the motion of the electrons and that it led to nonsense. So, they invented "quantum mechanics" which gives the appropriate description of the dynamics of the microscopic world. This was a true conceptual revolution as important as the revolution of special and general relativity. One of the main predictions of quantum mechanics is the quantization of physical quantities, and in particular the quantization of energy.

In the rest frame of the atom (frame where the center of mass of the atom, which practically coincides with the nucleus because the nucleus is much heavier than the electrons, is at rest), it appears that the energies of the electrons can only take discrete values, labelled by "quantum numbers". Figure 1 pictures, for example, three different atomic energy levels: the lowest energy level called ground state, the first excited level, the second excited level.

2.3 *Atom-Photon interactions*

How do atoms interact with light?

Emission and absorption of light by atoms.

An atom initially in a state E_b can jump from this level to a lower level

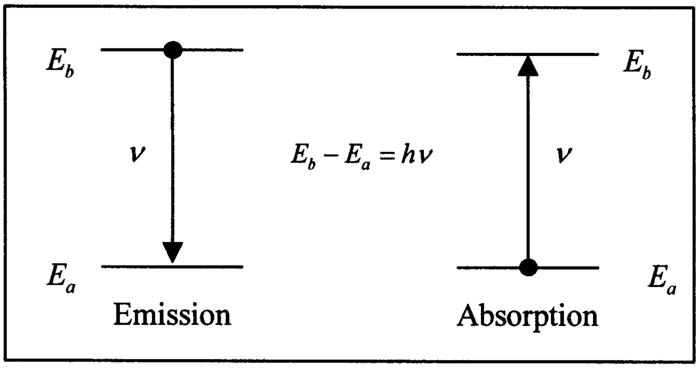


Figure 2: Elementary processes of emission (left part of the figure) and absorption (right part) of a photon by an atom.

E_a emitting light or more exactly emitting a single photon of energy $h\nu$ (Fig. 2). In other words, the energy lost by the atom passing from level E_b to level E_a is taken away by the photon of energy $h\nu$.

The relation between the energy lost by the atom and the frequency of the light being emitted is nothing but the expression of the conservation of energy.

The reverse process exists too, of course: the absorption of light by an atom. An atom initially in a lower state E_a can jump to an upper state E_b while gaining the energy of the absorbed photon. In other words, the atom absorbs a photon and the energy of the absorbed photon allows the atom to go from E_a to E_b. It thus clearly appears that the quantization of atomic energy implies the discrete character of the spectrum of frequencies emitted or absorbed by an atom.

Light: a main source of information on the structure of atoms

The only possible frequencies emitted by an atom are those corresponding to the energy differences between pairs of energy levels of this atom. This result is very important. It means that light is an essential source of information on the atomic world. Indeed, by measuring the frequencies emitted or absorbed by an atom, it is possible to determine the differences $E_a - E_b$ and thus to obtain the energy diagram of this atom. This is what is called “spectroscopy”. Each atom has its own spectrum. The frequencies emitted by a hydrogen atom are different from those emitted by a sodium or a rubidium or a potassium atom. The spectrum of frequencies emitted by an atom is in some way the finger print of this atom, or using more recent terms, its "genetic fingerprint". It is possible to identify an atom by observing the frequencies being emitted by this atom. In other words, it is possible to collect information on the constituents of different types of media by observing the light originating from these media. In astrophysics, for example, spectroscopy allows scientists to attain a deeper level of understanding of the structure of stellar and planetary atmospheres and to identify molecules within interstellar space. The observation of the frequency shifts of the radiation emitted by astrophysical objects allows a better knowledge of the velocity of these objects and makes it possible to measure with higher precision the expansion velocity of the universe. The observation of the emission or absorption spectra is also important for studying media such as plasmas or flames and for analysing their constituents *in situ*.

Radiative lifetime

Let us consider an isolated atom in an excited state E_b. Experiment shows that, very shortly, the atom spontaneously falls down to a lower state E_a. This period of time, at the end of which the emission process occurs, is called "radiative lifetime" t_R of the excited state E_b. It thus appears that an atom cannot remain in the excited state forever. Radiative lifetimes, which vary from one atom to another, are typically on the order of 10^{-8} s , that is 10 billionth of a second.

3. PRINCIPLES OF LASER COOLING

To cool an atom, one must reduce its velocity (more precisely, the dispersion of this velocity around its mean value). In laser cooling methods, this is achieved by radiative forces exerted by the laser beams on the atoms. We first analyse the origin of these radiative forces.

3.1 *Recoil of an atom emitting or absorbing a photon.*

Conservation of linear momentum is a basic law in physics. Consider an excited atom, initially at rest, in an upper state E_b, and suppose that at a certain time, this atom emits a photon with momentum $h\nu/c$. In the initial state, the total momentum of the system is equal to zero. In the final state,

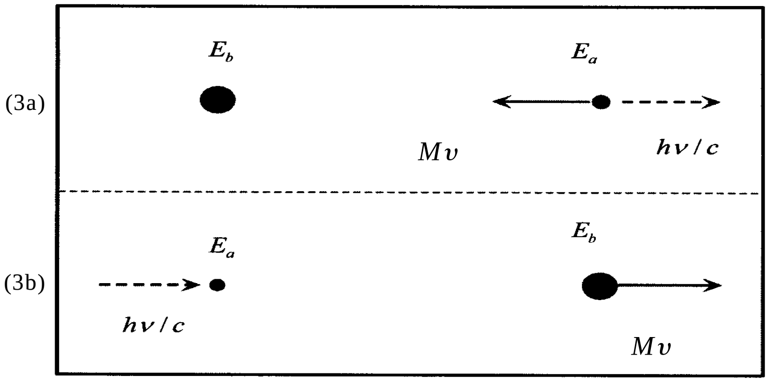


Figure 3: Recoil of an atom emitting (Fig. 3a) or absorbing (Fig. 3b) a photon.

when the photon moves away with momentum $h\nu/c$, the atom which has emitted this photon must recoil with the opposite momentum $Mv=-h\nu/c$ because of the conservation of momentum (Fig. 3a). The same phenomenon is observed, for example, when a gun fires a shell. The gun recoils and this recoil is due to the momentum transferred by the shell. The recoil velocity of the atom is given by $v_{\text{rec}}=h\nu/Mc$.

This recoil phenomenon also occurs when an atom absorbs a photon. Consider an atom initially at rest in the ground state E_a and suppose that a photon is being sent on this atom. What happens then? The atom absorbs the photon, jumps to the excited state and then recoils with the same recoil velocity $h\nu/Mc$ (Fig. 3b). Likewise, when a bullet is being shot on a target, the target recoils because of the momentum transferred by the projectile.

We also know that the absorption of a photon which brings the atom, initially at rest, to the excited state, is necessarily followed by an emission since the atom cannot remain excited forever. Therefore, after a very short time corresponding to its radiative lifetime, the atom falls down while emitting spontaneously a photon. In such an absorption-emission cycle, the atom absorbs a photon, it recoils and then emits a photon, the probabilities of the photon being emitted in one direction or in the opposite one being equal so that the momentum lost during emission averages out to zero. It follows that, in an absorption-emission cycle, the average variation of the atomic velocity is only related to the absorption process. Its value is $v_{\text{rec}}=h\nu/Mc$. This result is essential for the discussion of the next section.

3.2 *Atom in a laser beam*

We try now to understand what happens when the atom interacts, not with a single incident photon, but with a resonant laser beam. The atom absorbs a photon, jumps to the excited state, falls back to the ground state while emitting a photon, then absorbs a second photon, jumps to the excited state, falls back again while emitting another photon, then absorbs a third photon and so on. The atom thus performs a sequence of absorption-emission cycles. During each absorption-emission cycle, the velocity of the atom changes on the average by an amount $\upsilon_{\text{rec}} = h\nu/Mc$. As the average radiative lifetime of an atom in the excited state is on the order of 10^{-8} s, about 10^8 (one hundred million!) absorption-emission cycles can take place per second. After each of these cycles, the velocity of the atom changes by an amount $h\nu/Mc$. For a sodium atom, one finds that $\upsilon_{\text{rec}} \simeq 3$cm/s, whereas for a cesium atom $\upsilon_{\text{rec}} \simeq 3$mm/s. These are very low velocities compared to those of the molecules within the air surrounding us, which are on the order of 1 km/s. This explains why the velocity changes due to recoil effects have been most of the time neglected. In fact, the situation proves to be radically different for an atom in a laser beam. Absorption-emission cycles are then repeated 100 millions times per second, causing a velocity change per second which amounts to 100 millions times the recoil velocity, corresponding to an acceleration or a deceleration γ on the order of 10^6 m/s^2. Let us compare, for example, with what happens in our daily life: an object, when falling, is subjected to an acceleration g of 10 m/s^2 because of gravity. A sodium atom, when irradiated by a laser beam undergoes an acceleration or a deceleration γ which is 10^5 times higher!

3.3 *Stopping an atomic beam*

This considerable force exerted on atoms by light and resulting from the cumulative effect of a great number of slight recoils, makes it possible to stop an atomic beam. Consider an atomic beam coming out of an oven at a temperature of 300 K or 400 K. It propagates at a speed of the order of 1 km/s. Let us assume that this atomic beam is irradiated by a counter-propagating resonant laser beam. The atoms are then subjected to the radiation pressure force exerted by the laser beam, they slow down, they stop and they can even return in the opposite direction. An atom, with an initial velocity $\upsilon_0 = 10^3$ m/s, submitted to a deceleration $\gamma = 10^6$ m/s^2 will be stopped in 10^{-3}s, that is to say in one millisecond. The distance L travelled by this atom before stopping is given by a well-known formula $L=v_0^2/2\gamma$ and is equal to 0.5 m. It is thus possible, in a lab, to stop an atomic beam within a distance of the order of 1m with appropriate laser beams.

One must not forget however that, as atoms decelerate, they get out of resonance because of the Doppler effect. It is thus necessary to modify either the frequency of the laser beam or the frequency of the atoms to maintain the resonance condition and to keep the radiation pressure force at its highest level throughout the whole deceleration process.

Slowing down atoms consists in lowering the average velocity of these atoms. A clear distinction must be made between the global movement of an ensemble of atoms characterized by the mean velocity and the dispersion of velocities around this mean value. In physics, temperature is associated with this velocity spread, *i.e.* with the disordered motion of the atoms. The warmer the temperature of the medium, the higher the velocity dispersion of its constituents. For cooling a system, this velocity spread has to be reduced. How is it possible to cool atoms with laser light?

3.4 *Doppler cooling*

The simplest cooling scheme uses the Doppler effect and was first suggested in the mid seventies by Hansch, Shawlow, Wineland and Dehmelt. The concept is basically simple: the atom is then no longer irradiated by one laser wave but by two counter-propagating laser waves (Fig. 4). These two laser waves have the same intensity and the same frequency ν_L, ν_L being tuned slightly below the atomic frequency ν_A. What happens then? For an atom at rest with zero velocity, there is no Doppler effect (Fig. 4a). The two laser waves have then the same apparent frequency. The forces being exerted have the same value with opposite signs. The two radiation pressure forces coming from each side exactly balance each other and the net force exerted on the atom is equal to zero. For an atom moving to the right with a velocity v, the frequency of the counter-propagating beam seems higher because of the Doppler effect. This apparent frequency, which is thus increased, gets closer to resonance. More photons are absorbed and the force increases. On the other hand, the apparent frequency of the co-propagating wave is reduced because of Doppler effect and gets farther from resonance. Less photons are absorbed and the force decreases. In that case, the two radiation pressure forces no longer balance each other. The force opposite to the atomic velocity finally prevails and the atom is thus submitted to a non-zero net force opposing its velocity. This net force F can

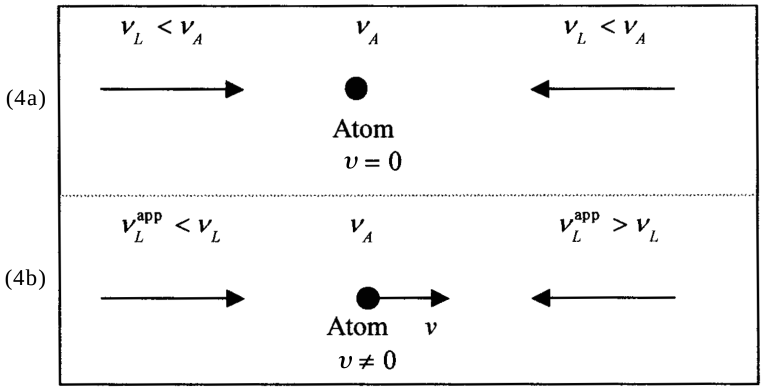


Figure 4: Principle of Doppler laser cooling. For an atom at rest (Fig. 4a), the two radiation pressure forces exactly balance each other. For a moving atom (Fig. 4b), the apparent frequency of the counter-propagating wave increases and gets closer from resonance. It exerts a stronger radiation pressure force on the atom than the co-propagating wave, whose apparent frequency is decreased because of the Doppler effect and gets farther from resonance.

be written for a small velocity v as $F = \alpha v$ where α is a friction coefficient. In other words, an atom moving in such an arrangement of two counter-propagating laser beams encounters a friction force opposing its motion. It finally gets stuck as if it was moving in a sticky medium which has been called "optical molasses" by analogy with honey. The atomic velocity is damped out by this force and tends towards zero.

3.5 *Sisyphus cooling*

By studying theoretically the Doppler laser cooling mechanism, it has been possible to predict the temperatures that may be achieved. These are on the order of a few hundreds of microkelvin, *i.e.* on the order of 10^{-4} K. These are very low temperatures compared to room temperatures which are on the order of 300 K. In fact, when, at the end of the eighties, the measurements became precise enough, it turned out, and that was a real surprise, that the temperatures in optical molasses were 100 times lower than expected, meaning that there were other mechanisms at work. We have, with my colleague Jean Dalibard, identified and studied in detail one of these mechanisms: Sisyphus cooling.

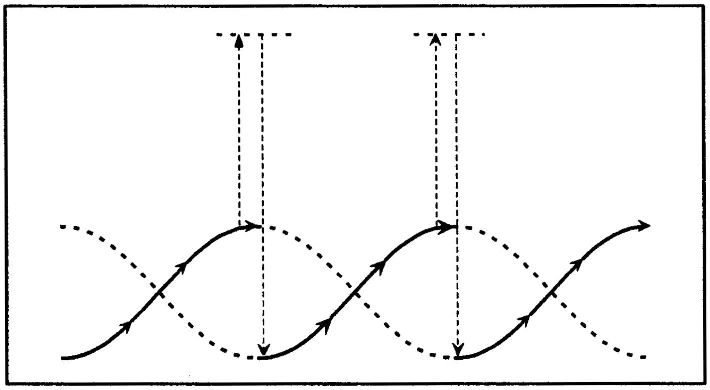


Figure 5: Sisyphus cooling.

Without exploring all the details of such a mechanism, let us try now to describe briefly how it works. Laser cooling experiments use pairs of counter-propagating waves. These waves interfere and produce a standing wave with spatially modulated intensity and polarization. One can also demonstrate that atomic energy sublevels are slightly shifted by light, by an amount proportional to light intensity and related to light polarisation. Moreover, in the ground state, there are in general several energy sublevels, corresponding to different quantized values of the projection of the atomic angular momentum along a given axis. The atom can be considered as a small spinning top. In the simplest case (spin 2), there are two spin states: spin up and spin down. Such energy levels, with spatially modulated light-shifts, are represented in Fig. 5. The moving atom runs up and down potential hills and valleys. This landscape changes according to the different atomic sublevels. Consider an atom moving to the right, initially at the bottom of a potential valley in a specific sublevel, and then climbing up the potential hill. When it reaches the top of the hill, it has a high probability to absorb and emit a photon and thus to move to the other energy sublevel, being then put back at the bottom of the next valley. This scenario can repeat itself, the atom climbs up another potential hill and, before reaching the top, is transferred again to the other sublevel and so on, again and again...Like the hero of the Greek mythology, the atom is doomed to a continual climbing of hills, losing kinetic energy as it climbs. After a while, the atom is so exhausted that he can no more run up hills and finally gets trapped in a well. Theoretical studies combined with experimental results have confirmed the validity of this picture and shown that it is possible in that way to reach the microkelvin range, *i.e.* a temperature of 10^{-6} K. We have also finalized other methods in the lab leading even further, to the nanokelvin range, *i.e.* 10^{-9} K, one billionth of Kelvin...

At such temperatures, atomic velocities are on the order of cm/s or even mm/s whereas, at an usual room temperature, they are on the order of km/s. These cooling methods have made it possible to slow down considerably the disordered motions of atoms and almost to stop them. Let us mention too, without going into details, that atoms can be confined in small spatial regions, called traps, by using laser polarization gradients or magnetic field gradients.

4. A FEW APPLICATIONS OF ULTRACOLD ATOMS

4.1 *Atomic clocks*

Ultracold atoms move very slowly. For example, Cesium atoms cooled by Sisyphus cooling have a velocity on the order of 1 cm/s. This allows them to spend a longer time T in an observation zone where a microwave field induces resonant transitions between two sublevels g_1 and g_2 of the ground state which are used to define the unit of time: the second. By convention, the second corresponds to 9 192 631 770 periods of oscillations $1/\nu_0$, where ν_0 is the frequency of the transition connecting g_1 and g_2. The important point here is that the width $\Delta\nu$ of the microwave resonance line whose frequency is used to define the unit of time is inversely proportional to the observation time T. Long observation times give rise to narrow atomic resonance lines allowing a very precise determination of the atomic frequency ν_0. The stability and accuracy of atomic clocks can thus be considerably improved by using ultracold atoms.

In usual atomic clocks, atoms from a thermal cesium beam. cross two microwave cavities fed by the same oscillator. The average velocity of the atoms is several hundred m/s, the distance between the two cavities is on the order of 1 m. The microwave resonance between g_1 and g_2 is monitored and is used to lock the frequency of the oscillator to the center of the atomic line. The narrower the resonance line, the more stable the atomic clock. In fact, the microwave resonance line exhibits Ramsey interference fringes whose width $\Delta\nu$ is determined by the time of flight T of the atoms from one cavity to another. For the longest devices, T, which can be considered as the observation time, can reach 10 ms, leading to values of $\Delta\nu$ on the order of 100 Hz.

Much narrower Ramsey fringes, with sub-Hertz line-widths can be obtained in the so-called “Zacharias atomic fountains”. Atoms are captured in a magneto-optical trap and laser cooled before being launched upwards by a laser pulse through a microwave cavity. Because of gravity they are decelerated, they return and fall back, passing a second time through the cavity. Atoms therefore experience two coherent microwave pulses, when they pass through the cavity, the first time on their way up, the second time on their way down. The time interval between the two pulses can now be on the order of 1s, i.e. about two order of magnitudes longer than with usual clocks. This explains how the stability and accuracy of atomic clocks have been recently improved by two orders of magnitude by using fountains of cold atoms.

To increase the observation time beyond one second, a possible solution consists of building a clock operating in a reduced gravity environment. Tests have been performed with an experimental set-up embarked in a plane making parabolic free flights. These tests have been successful and it is planned now to put such a cold atom clock in the International Space Station around 2005.

Atomic clocks working with ultracold atoms can of course provide an improvement of the Global Positioning System (GPS). They could also be used for basic studies. A first possibility could be to build two fountains clocks, one with Cesium and one with Rubidium, in order to measure with a high accuracy the ratio between the hyperfine frequencies of these two atoms. Because of relativistic corrections, the hyperfine frequency is a function of $Z\alpha$, where α is the fine structure constant and Z is the atomic number. Since Z is not the same for Cesium and Rubidium, the ratio of the two hyperfine frequencies depends on α. By making several measurements of this ratio over long periods of time, one could check cosmological models predicting a variation of α with time. The present upper limit for $\dot{\alpha}/\alpha$ in laboratory tests could be improved by two orders of magnitude. Another interesting test would be to measure with a higher accuracy the gravitational red shift and the gravitational delay of an electromagnetic wave passing near a large mass (Shapiro effect).

4.2 *Atomic interferometry*

Wave-particle duality applies not only to light but also to matter. In 1924, Louis de Broglie introduced the idea that a wave, called since then the de Broglie wave, must be associated with every material particle. For a particle with mass M, the wavelength of this wave, the so-called de Broglie wavelength λ_{dB}, is given by the equation $\lambda_{\mathrm{dB}} = h/Mv$, where v is the velocity of the particle. When the velocity decreases, the de Broglie wavelength increases and several effects related to the wave nature of atomic motion become important and easier to observe.

New research fields, like atom optics and atom interferometry, have thus experienced during the last few years a considerable development, extending to atomic de Broglie waves the various experiments which were previously achieved with electromagnetic waves. For example, Young fringes have been observed by releasing a cloud of cold atoms above a screen pierced with two slits. The impact of the atoms on a detection plate is then observed giving a clear evidence of the wave-particle duality. Each atom gives rise to a localized impact on the detection plate. This is the particle aspect. But, at the same time, the spatial distribution of the impacts is not uniform. It exhibits dark and bright fringes which are nothing but the Young fringes of the de Broglie waves associated with the atoms. Each atom is therefore at the same time a particle and a wave, the wave allowing one to get the probability to observe the particle at a given place.

In contrast to light interferometers, atomic wave interferometers are sensitive to gravitational effects which can be measured with a great accuracy. The equivalent of the Sagnac effect for light has been observed with atomic de Broglie waves. The inherent sensitivity of such “atomic gyrometers” can exceed that of photon gyrometers by a very large factor. This is due to the fact that slow atoms spend a much longer time in the interferometer than photons. Other interesting applications have been developed, like atom lithography, which allows atoms to be deposited on a substrate to form controlled structures with a resolution of a few tens of nanometers.

4.3 *Bose-Einstein Condensation*

At very low temperatures and high densities, the average distance between atoms can become comparable to the de Broglie wavelength. Equivalently, the phase space density $n\lambda_{\mathrm{dB}}^3$, where n is the number of atoms per unit volume, can become larger than 1. In this regime, where the wave packets of the atoms overlap, spectacular effects can occur as a consequence of the symmetry properties of the wave function describing an ensemble of identical particles. Bosons trapped in an external potential are predicted to condense in the quantum ground state of the trap.

Up to now, the only evidence for such an effect, called Bose-Einstein Condensation (BEC), came from studies on superfluid liquid Helium and excitons in semiconductors. The strong interactions which exist in such systems modify qualitatively the nature of the condensation. A great challenge was therefore to observe BEC in an ultracold dilute atomic gas where interactions are much weaker. Great efforts have been devoted to observing BEC in spin-polarized hydrogen, which is the only quantum gas to remain gaseous at absolute zero. New techniques for cooling and trapping atomic gases have been developed, such as evaporative cooling and magneto-static trapping. Phase space densities very close to 1 have been achieved.

Only within the last few years has it been possible, by combining laser manipulation techniques with evaporative cooling and magneto-static trapping, to observe BEC on alkali atoms, such as rubidium, sodium, lithium. A new exciting research field has been opened by these experiments. All condensed atoms are described by the same wave function, giving rise to macroscopic matter waves with remarkable quantum properties (coherence, superfluidity...) which have been observed and studied in great detail. Coherent sources of atoms, called “atom lasers”, are obtained by extracting atoms from a condensate with various types of output couplers. They can be considered as the equivalent, for de Broglie waves, of lasers for electromagnetic waves, and spectacular advances are expected when these sources will become operational and will be used for atomic interferometry.

5. Conclusion

The investigations about the nature of light and its interactions with matter have led to spectacular scientific advances during the last century. A new understanding of the microscopic world has emerged with the development of quantum mechanics. Wave-particle duality has been extended to all physical objects. New light sources, with remarkable properties, the lasers, have been invented.

It has also been realised that light is not only a source of information on the structure of atoms, but also a tool for acting on these atoms. Various methods, like optical pumping, laser cooling and trapping have been developed for controlling the various degrees of freedom of an atom. This increased control of light-matter interactions opens new perspectives for research. New physical objects, like matter waves, atom lasers, degenerate quantum gases, have appeared. Some applications of these scientific advances are still to come. They will, hopefully, open new avenues for Science during the new century.

BIBLIOGRAPHY

S. Chu, “The manipulation of Neutral Particles”, *Rev. Mod. Phys.* 70, 685 (1998).
C. Cohen-Tannoudji, “Manipulating Atoms with Photons”, *Rev. Mod. Phys.* 70, 707 (1998).
W.D. Phillips, “Laser Cooling and Trapping of Neutral Atoms”, *Rev. Mod. Phys.* 70, 721 (1998).

The author thanks Nadine Beaucourt for her help in the preparation of this manuscript.

THE RELATIONSHIP BETWEEN SCIENCE, RELIGION AND ARISTOTELIAN THEOLOGY TODAY

ENRICO BERTI

1. *The Relationship between Science and Religion*

Many scientists, philosophers and theologians maintain that there exists a relationship of 'consonance' between science and religion today, and that this is not based, as in the past, on the fact that there may be some problems which have as yet not been solved by science and which might have a religious solution. They think that through the methods of contemporary science it is possible to admit, in a probable, if not in a necessary way, the existence of God and the creation of the world by Him. This is the case, for instance, of Richard Swinburne, who thinks that the existence of God, from the point of view of the calculus of probabilities, is the simplest and therefore the most probable hypothesis for the explanation of the world, as it is known by science.[1] In an analogous way, John Polkinghorne thinks that the world's creation by God is compatible with a physical theory of the stationary universe as well as with a scientific conception of its origin, both where this origin is conceived as involving an initial 'big bang' and where it is conceived as involving a quantistic fluctuation of an 'inflated *vacuum*'. Moreover, Polkinghorne believes that the apparently anthropic direction of evolution can also be explained by a scientific theory of an 'informational, not energetic, agency' of God.[2]

Some of the contents of Christian faith, indeed, cannot be explained from a scientific point of view. Furthermore, they cannot be accepted by

---

[1] See R. Swinburne, *The Existence of God* (Oxford University Press, 1979).

[2] See J. Polkinghorne, *Belief in God in the Age of Science* (Yale University Press, 1998).

science because they seem to contradict the laws of nature, even where these are conceived in an indeterministic or a probabilistic way. I am thinking, for instance, of the resurrection of Jesus Christ, or of the virginity of Mary and her maternity in relation to Christ, which seem to contradict the laws of biology, and also of many other miracles. In these cases it is not enough to appeal to a simple act of faith, because Christian faith, as the Pope said in his last encyclical *Fides et Ratio*, cannot be faith in the absurd, i.e. in the impossible. Even those scientists and theologians mentioned above admit that between science and religion there must be a relationship of consonance, i.e. of compatibility. And the existence of any contradiction would violate this relationship.

In order to eliminate these contradictions, and to ensure the compatibility of science and religion, it is necessary to admit the dependence of nature on an absolute power which can make exceptions to the laws of nature, i.e. the same kind of dependence which is involved in the notion of creation, as stated by the Bible. Now, the concept of creation, considered in the sense of a total dependence of the universe on a transcendent God, even purified of those mythical characters which are described in the Bible, can certainly be accepted by an act of faith, but this presupposes some necessary conditions. And the absence of these conditions makes faith absurd and unacceptable from any point of view.

2. *The Conditions of Consonance*

In my opinion, these conditions are the following:

1. The existence of an absolute, i.e. infinite, power, which does not depend on any other being and on which every other being depends;
2. the transcendence, i.e. the difference, the complete heterogeneity, of a being which possesses such a power in relation to nature, i.e. in relation to the universe, including mankind, with its history, its culture, its science, and its technology;
3. the characteristic of intelligence of this being, which gives him the capacity to think, will, and act.

The first of these conditions, i.e. the existence of an absolute power, is necessary in order to explain the exceptions to the laws of nature because only the power that created these laws can violate or suspend them. But this means that there must be something, or someone, which or who is superior to nature because it or he is not subject to its laws. This means, therefore, that nature, or the universe, or the infinite multiplicity of worlds – in other words the reality which is the object of our scientific investigations – is not the whole of reality. There must be something else upon which that reality which is the subject of science depends. Obviously, I am not claiming here that this something else does necessarily exist (this is a philosophical problem and would need a wider discussion) but I am saying that its existence is necessary in order to ensure a consonance between science and religion.

The second condition, i.e. the transcendence of a being who possesses absolute power, is necessary because if the power capable of making exceptions to the laws of nature was immanent, i. e. internal, to nature, it would be a part of it, and therefore the same nature would on the one hand be governed by some laws and on the other hand it would be capable of making exceptions to them, and this would be a contradiction. It is true that for some scientists many events in nature, even biological evolution, depend only on chance. But in this case chance would itself be a law of nature, and in this respect the events mentioned above – the resurrection of Christ, the virginity of Mary – would be exceptions and therefore impossible. I do not believe, in fact, that those scientists who believe that natural phenomena are due to chance would admit the possibility, through chance, of miracles. Even if we imagine an immense human power, capable of going beyond the laws of nature that we know so far, this power would be a part of nature and would be subject to its general laws. Thus, even this immense power could not explain the events which are apparently in contrast with the general laws. If it could, it would be a magical power incompatible with science.

The third condition, i.e. the intelligence of a being provided with absolute power, is the most evident, because only an intelligent being capable of thinking and willing can act on nature and on history in an intentional way, in a way which is required to explain the events mentioned above. On the other hand, every kind of religion (at least religions inspired by the Bible) believes in the existence of an intelligent and willing God, but the condition for this belief, which is faith, is the possibility of conceiving of such a being in a rational way, or at least in a way which is not in contrast with reason. All these conditions – and this is my point – are not a question of religion (i.e. of faith in divine revelation, because these conditions are also the conditions for the possibility of revelation itself), or of science, because they go beyond the field of scientific investigation.

Therefore, they are part of a discourse which is neither religion nor science, a discourse which we can refer to by no other name than philosophy, or better, a particular type of philosophy – metaphysics – or better still a particular type of metaphysics, i.e. the metaphysics of transcendence.

3. *Aristotelian Theology*

As a matter of fact, all these conditions were arrived at by a philosopher who did not know the Bible and who was not influenced by it in any sense – Aristotle. He arrived at these conditions through a process which he claimed to be rational, i.e. philosophical. This process may be criticised from a philosophical point of view, or, in contrary fashion, it may be accepted as a valid philosophical demonstration. This is an open question at the level of philosophical discussion. But, whatever the case, this process was historically located within a philosophical context and it was totally uninfluenced by any kind of religious faith. In the view of philosophers who have believed in religions based upon by the Bible – Jews (such as Avicebron and Maimonides), Muslims (such as Alfarabi, Avicenna, and Averroes) and Christians (such as Albert the Great and Thomas Aquinas) – Aristotle's formulation of these conditions was a necessary premise to religious faith. A necessary premise from a logical point of view and not from a psychological point of view, although obviously it was not a sufficient premise.

The 'unmoved mover' (whether one or more than one), whose existence Aristotle tries to demonstrate in the twelfth book of his *Metaphysics* (i.e. through so-called 'Aristotelian theology'), has an infinite power because – as Aristotle explicitly affirms – it has the capacity to move the heavens for an infinite time (cp. 1073 a 8-9); it is transcendent in relation to every other being because it is the only unmovable being, whereas all the other beings are moved (1071 b 17-20); and it is intelligent because it thinks (the act of thinking is its self being, it is its self essence) and it wills (as is proved by the fact that, according to Aristotle, it is happy). It also has the capacity to act because – as I have tried to demonstrate in many works – it is not only a final cause but also an efficient cause of the movement of the heavens.[3]

---

[3] See E. Berti, 'Da chi è amato il motore immobile? Su Aristotele, Metaph. XII 6-7', *Méthexis. Revista Argentina di Filosofia Antigua*, X, 1997, pp. 59-82; 'De qui est fin le moteur immobile?', in M. Bastit ed J. Follon (eds.), *Essais sur la théologie d'Aristote* (Louvain-la-Neuve, 1998), pp. 5-28; 'The Unmoved Mover as Efficient Cause in Aristotle's *Metaph*. XII', in M. Frede and D. Charles (eds.), *Aristotle's Metaphysics Lambda* (Oxford, 2000), pp. 181-206.

Therefore, according to Aristotle, 'he' – we can now use the personal pronoun because we are speaking about a person – is a God, and this is a consequence of the fact that he is eternal and happy (these are the characteristics that ancient Greeks attributed to gods), even if he is not a creator God (1072 b 26-30).

Obviously, I am not claiming that Aristotle's unmoved mover is the same as the God of the Bible: as I have already observed, he is not a creator God. For Aristotle he is just a mover, even if by moving the heavens he is the cause of every generation and corruption on the earth, i.e. of the life and death of every living being. And he has not revealed himself to man: Aristotle is not aware of divine revelation. Perhaps – but this is not certain – he does not know or love man. In some passages Aristotle seems to think that God knows and loves only himself, but at other points he affirms that wise men are loved by gods. Therefore Aristotle's God does not have sufficient characteristics to be the same as the God of the Bible. But the characteristics he does have, i.e. transcendence, intelligence, infinite power, are necessary to being the God of the Bible in the sense that they are the necessary conditions for a creator God. From a philosophical point of view, it is important to add that Aristotle's unmoved mover has an advantage that the God of the Bible does not have – i.e. he was not known because of an act of revelation but was discovered by a philosopher through human instruments alone, i.e. observation, reflection, and reasoning.

4. *The Necessity of Metaphysics*

My aim here is not the defence of Aristotelian theology as it was historically developed. Nevertheless, I believe that in order to ensure compatibility between science and religion it is necessary to have a form of metaphysics of the kind to be found in Aristotelian theology – i.e. a form of metaphysics which admits the transcendence of the Absolute. This theology, or rather, this form of metaphysics, is termed 'Aristotelian' perhaps because Aristotle was the only philosopher who was not influenced by the Bible and yet reached the idea of a transcendent God by rational paths. This form of metaphysics does not seek to demonstrate the validity of the contents of religious faith but it does allow us to establish the logical conditions for their possible existence, i.e. to create a sort of space which goes beyond science. Without this space religion would be impossible. In order to believe in religious meaning it is not necessary to profess this form of metaphysics explicitly, but this kind of metaphysics is necessarily involved, from a logical point of view, in every authentic act of religious faith.

This is a very poor form of metaphysics because it does not include the whole of ‘natural theology’ as developed by Christian (but also by Jewish and Muslim) philosophers during the Middle Ages (but also during the modern age). This kind of metaphysics could be defined ‘weak’ metaphysics from an epistemological point of view, i.e. in the same sense in which scientific theories with a poor cognitive content are called ‘weak theories’. The fundamental idea of this form of metaphysics, in fact, is based on the idea that the world of our experience, which forms the object of our scientific investigations, does not coincide with the whole of reality. For this reason, the world of the experience is not an absolute world, it is not self-sufficient, and it does not have within itself everything that is necessary for its explanation. We would say that this metaphysics only creates a space. But, precisely in virtue of its weakness, this form of metaphysics is very strong from a logical point of view because it is extremely difficult to refute it. In order to refute it, in fact, it would be necessary to demonstrate that the world of our experience can be completely explained by some factors which are immanent to it, i.e. that it is an absolute – a result that a scientific theory could hardly aspire to obtain.

To tell the truth, at the end of the twentieth century the main alternative advanced by scientists to the metaphysics of transcendence, i. e. to theism, is not a metaphysics of immanence, of the same kind of positivism, or materialism, as was evident in the nineteenth century. At the end of the twentieth century a large proportion of scientists think that the alternative to metaphysics is an appeal to pure chance. This is the thesis that the whole universe, with its present structure and order, including the existence of life and man, is the result of an infinite series of changes which are exclusively due to chance. This position seems to me to be an abandonment of an exhaustive explanation rather than a claim to a perfect explanation of the universe through reference to its internal factors. But, in fact, if chance is considered the only possible explanation for the universe, it becomes an exhaustive explanation, i.e. an explanation which considers the universe as perfectly self-sufficient and does not admit further research, an explanation which is completely self-sufficient.

This kind of approach, it seems to me, is the negation not only of the philosophical spirit but also of scientific research and in general of any critical sense. The existence itself of science and philosophy, and their continual and perhaps infinite desire for knowledge is the best refutation of this approach. This never satisfied desire for knowledge, like the awareness of an incomplete and inadequate explanation of the universe, is not only a requirement of human reason, but – in a realistic perspective, which is the prevailing attitude of scientists – it corresponds to a real feature of the universe itself, i.e. to its inability to explain itself completely, to having within itself all those factors which are necessary to its complete explanation. In this way, the metaphysics of transcendence turns out to be not only the necessary condition for compatibility between science and religion, but also the necessary condition for a genuine scientific approach towards the universe, i. e. a fair admission of the problematic character of our experience of the world.

DESIGN VERSUS SELECTION IN CHEMISTRY AND BEYOND

ALBERT ESCHENMOSER

Design is "a thing planned for, or an outcome aimed at" (Webster's dictionary). What is central to its nature is that it has the intentionality of a conscious being as its origin. Such can – but does not have to – be the case for *Selection*.

Examples of design range from the use of tools by primates in order to collect food, to the cultural interference of early humans with the natural growth of plants ("agriculture"), and on to the Hubble telescope and the world of modern technology that surrounds us.

Focusing in this paper on science and technology, the term "design" refers more to the realm of technology than to that of science. Normally, a design is a product of science, it has comprehensive and approved scientific knowledge as its prerequisite. Needless to say, more often than not an inextricable entanglement of a technology and the science it is derived from blurs the border between the two, and the history of science abounds with examples which show how progress in science can depend on the emergence of technologies. There are, of course, quasi-unlimited opportunities for human creativity in design, and there can be great art in it.

The "designedness" of the modern high-tech world mostly sprung from physics. What we call chemistry today was originally a field of experimental inquiry which the physicists of the eighteenth and nineteenth centuries "delegated", so to say, to specialists, because the phenomena observed in the metamorphoses of matter were so alien and so complex that they were not amenable to mathematical compression according to the state of the art in physics of that time. Today we know, mostly as a consequence of the workings of those specialists – the chemists – that this complexity is largely the reflection of an immense structural and behavioral diversity of molecules. “The molecule”, a central concept in the hierarchical description of matter, was unknown to the physics of that time.

Whenever the excessive complexity of phenomena surpasses the capacities of an established science that is dedicated to pursuing its traditional goals and successes, it is time for the birth of a daughter science. As with physics in the eighteenth century, the same happened to chemistry in the twentieth century. This time it was the complexity of the structure and functions of the macromolecular biomolecules inside and outside living cells that surpassed the capacities of chemists and, therefore, escaped their interest. Traditional chemists, busy with harvesting the fat crops of their field, had to leave the “chemistry of life” to the molecular biologists.

MOLECULAR DESIGN in CHEMISTRY

DESIGN of a SYNTHESIS

To conceive, within the constraints of chemical theory and experience, a synthetic pathway (type, sequence and conditions of a series of chemical reactions) that can be expected to lead to a specific molecular structure.

DESIGN of a MOLECULE

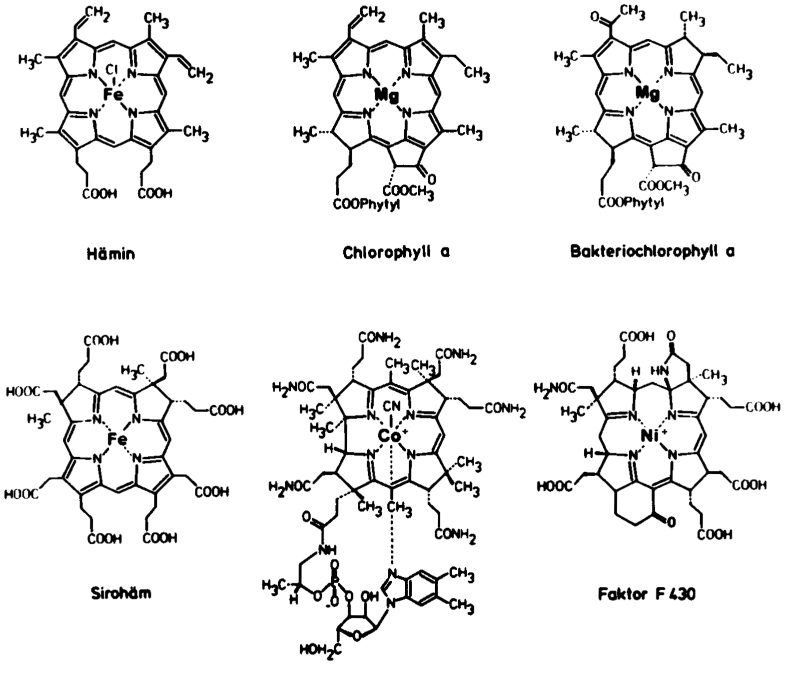
To conceive, within the constraints of chemical structure-theory, a (thus far) non-existing molecular structure.

DESIGN of SUPRA-MOLECULES and MATERIALS

Fig. 1. Design in chemistry.

Chemistry, particularly organic chemistry, has long been an *eldorado for design*. First, there is the *design of the synthesis of a molecule*: to conceive – within the constraints of chemical theory and experience – a synthetic pathway (type, sequence and conditions of a series of chemical reactions) that can be expected to produce a specific molecular structure from simpler molecular precursors.

Hardly anywhere else is the aforementioned entanglement of science and technology more pronounced than when a chemist synthesizes a molecule for the first time. The complexity in the behavior of organic molecules is such that the first execution of a complex synthesis based on design is almost always also a venture into the uncertain, an experiment run for finding out whether and under what conditions the elements of the design do correspond to reality. Science in chemical synthesis is a harsh battle for new knowledge fought out in those steps of the synthesis where the design turns out to be incomplete, misleading, or wrong. Misleading or wrong not as a consequence of weaknesses in the design as such, but misleading or wrong because of gaps in existing knowledge.



Hämin **Chlorophyll a** **Bakteriochlorophyll a**

Sirohäm **Faktor F430**

Vitamin B12

Fig. 2 Structure of Vitamin B12 (center below) and of important porphinoid biomolecules.

It is in the very nature of a design that it is done for a *purpose*. A traditional scientific objective of executing a synthesis is to extend the frontier of molecular complexity that separates what can and what cannot be done. This is chemical synthesis as a means by which to acquire new chemical knowledge. A perhaps special, yet nevertheless representative, example, is the chemical synthesis of Vitamin B12. There was never a need for producing this most complex of all vitamins by chemical synthesis – microorganisms produce it plentifully and cheaply – for its medical use, yet the questions were: could chemists do it? What is the sort of chemistry that would allow such a synthesis to be achieved? Is new chemistry needed?

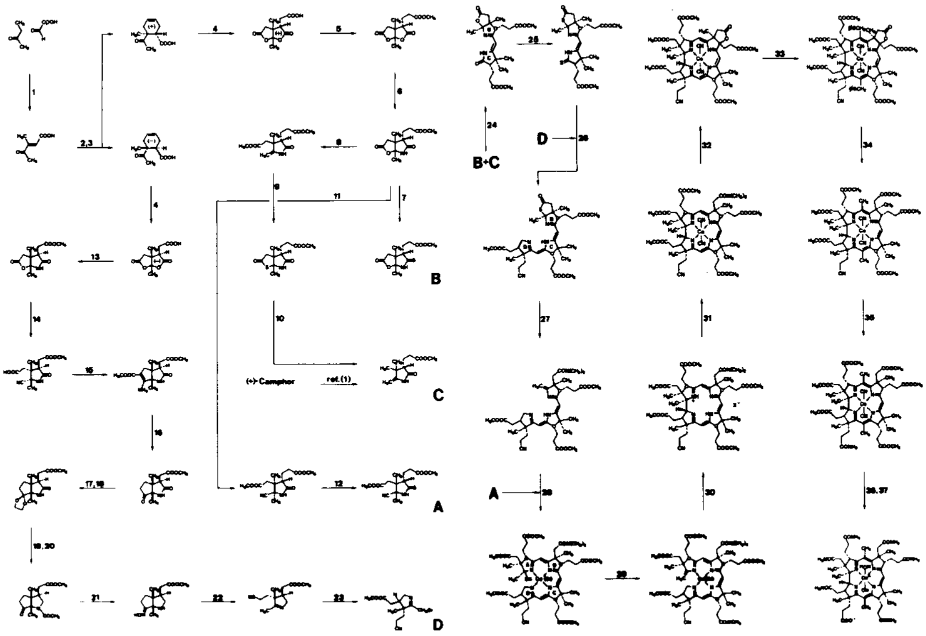


Fig. 3. Vitamin B12: An example of a chemical synthesis by design.

It was in fact in an complex interplay of synthetic design and chemical discovery that such new chemistry was uncovered. One of these discoveries even changed the way chemists think about chemical reactions. The chemical synthesis of vitamin B12 can also be said to have laid the final capstone on the grave of "chemical vitalism", the ancient belief that chemical substances occurring in the living world can only be produced by living organisms. Vitamin B12 was a contribution of chemistry to the ongoing process of demystifying living matter by science, a process that started in 1828 with the first chemical synthesis of a natural substance produced by animals – Wöhler's discovery of artificial urea.

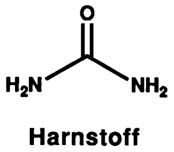


Fig. 4. Friedrich Wöhler (1828) discovered the first chemical synthesis of a natural product occurring in animals.

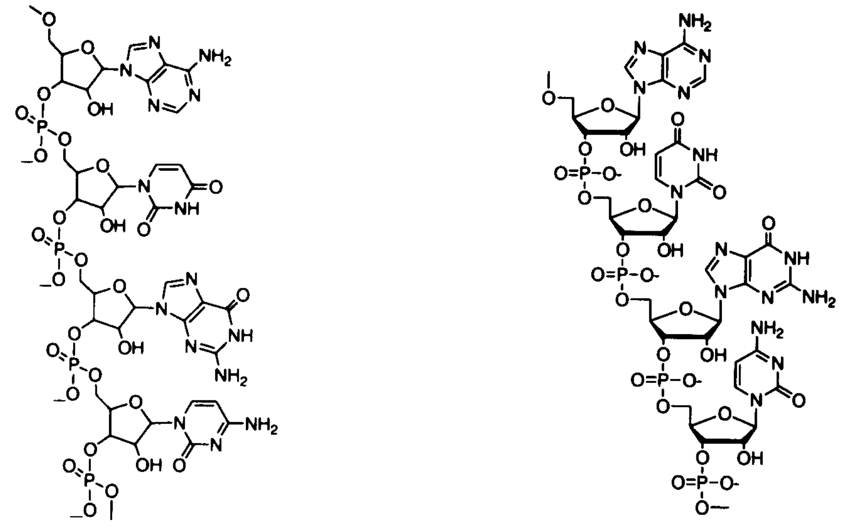
A century later, the process found its most dramatic expression in the landslide insights of molecular biology. And it is proceeding further, harshly enough, by what we are told is going to be possible in genetic engineering. The path from synthetic urea to partially synthetic organisms is a drama that, perhaps more than any of the other dramas in science and technology, reminds us how science is the force of our time that drives the expansion of mankind's consciousness.

There is another type of design in chemistry: *to design the structure of a molecule*, to imagine, to think of a new type of molecular structure, a molecule that may never have existed before. If such a design of structure is followed up by a design of its synthesis, then the execution of that synthesis amounts to the creation of a new piece of chemical matter (Fig. 5, see p. II).

For more than a hundred years chemists have known the program according to which molecules are built, the rules by which the laws of physics translate into the existence and behavior of molecules. The program is expressed in their global language of chemical formulas, a language that in its astonishing simplicity, as well as consistency, allows the prediction of the central property of virtually any aggregate of atoms such as carbon, oxygen, nitrogen, hydrogen etc., namely, whether such an aggregate has a chance of existing or not. Due to the practically unlimited compositional and structural diversity of molecules and the immense variety in the detail of their chemical properties, chemistry stands, in a way, continually at its beginning. Molecular diversity on our planet is breathtaking and fundamental at the same time, it is the foundation on which life is thriving. It is the immense diversity of structures as well as the diversity of the finest details in the behavior of complex macromolecules on the constitutional, conformational and constellational level which has made the evolution of chemical life on earth a contingency or, as some scientists dare to affirm, a necessity.

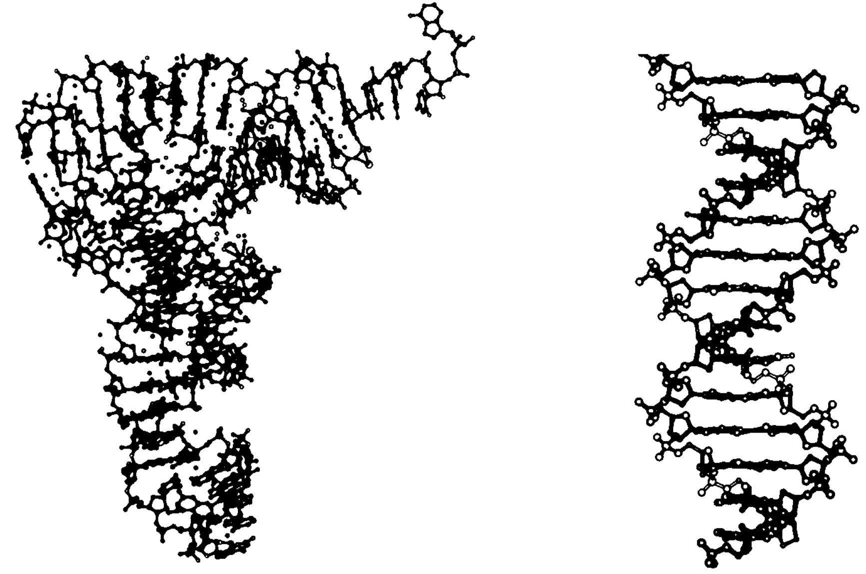
Organic chemistry has grown up with a long history of studying molecules discovered to occur in living nature. However there has always been,

MOLECULAR DIVERSITY



CONSTITUTIONAL

CONFIGURATIONAL



CONFORMATIONAL

CONSTELLATIONAL

Fig. 6. Four levels of describing the structure of biomolecules: Nucleic acids.

and still is, room for discovering molecules of the non-living world: C60, *Buckminster-fullerene*, is one of the most recent and most interesting examples (Fig. 7, see p. II).

The marvelous symmetrical structure of the football-shaped C60 structure had in fact been conceived and designed by chemists before its existence was discovered in interstellar space. But those designers had to abandon their quest of following up their design of a structure with a design of its synthesis. This brings us to a challenge chemists are confronted with today: the quest to make use of the intrinsic potential of molecules to self-assemble. Self-assembly is the coming into existence of a molecular (or supra-molecular) structure by a multi-step reaction path in a given environment without instruction from outside. C60 obviously has to self-assemble in interstellar space, otherwise it would not be there. Chemists grasped that lesson and learnt how to make the molecule on earth by setting up conditions under which in fact it assembles itself (condensation of vaporized carbon) (Fig. 8, see p. III).

Chemists distinguish two types of self-assembly, molecular and supramolecular, or constitutional and constellational. Either *molecules* assemble themselves from molecular or atomic components by reacting together and becoming joined through covalent bonds, or *supramolecular aggregates* assemble themselves from partner molecules by being held together through essentially non-covalent bonds, most often by so-called hydrogen bonds. The formation of C60 both in interstellar space and in the chemist's laboratory is an example of the first kind, the formation of the DNA double helix from DNA single strands both in living cells and in the chemist's laboratory is a – if not the – prototypical example of the second kind.

When we look at matters more closely, each multi-step chemical synthesis is actually to be seen as a succession of steps in which the chemist, at each step, sets the stage for a specific act of constitutional self-assembly to occur. Setting the stage means: creating the boundary conditions, the specific physical and chemical environment necessary for “the reaction to proceed”, providing the instruction the system requires in order to take over and to react in a specific direction. In a laboratory synthesis, it is the chemist who is the source of this instruction. In a multi-step biosynthesis proceeding in the living cell, the instruction is conveyed by the ambassadors of the genome, the enzymes that make a biosynthesis occur. The channel through which the instruction reaches the reaction partners is *catalysis* – positive catalysis that accelerates a specific reaction step or negative catalysis that slows it down. From a chemist's point of view, a multi-step biosynthesis amounts, in principle, to an overall constitutional self-assembly of the target molecule in a genome-controlled environment. Fundamentally, what living nature has so irresistibly explored in Darwinian evolution is the immense potential of the molecular world for constitutional and constellational self-assembly.

Constellational self-assembly is in the focus of interest today in structural biology as well as in chemistry. It was only about a year ago that we could marvel at the x-ray structures of a ribosome, the heart of biology, as some of us would say.

The ribosome is a constellational aggregate of more than fifty different protein – and RNA – molecules held together by non-covalent bonds in a specific arrangement relative to each other, and orchestrated for acting as a machine capable of decoding the information contained in genes by converting base-sequences of nucleic acids into amino-acid-sequences of proteins. Chemists are perhaps the most propitious people for judging how miraculously biological supramolecular systems such as the ribosome are actually built. This is because chemists, particularly synthetic chemists, in being confronted with such a structure react in a sort of reflex action by asking: “how would I make it?” The ribosome structure immediately gives them a lesson in modesty, by pointing to the breathtaking distance between the state of the art in what chemists might be able to achieve by design, and what biological evolution has accomplished (Fig. 9, see p. IV; Fig. 10, see p. III).

In basic chemical research, constellational self-assembly is today a central topic. On the other hand, besides the design of new molecular structures and the design of syntheses, the study of supramolecular aggregates is also the concern of chemists in more utilitarian areas of chemistry, namely in the factories of drug design. Traditionally, drug research was mostly concerned with the isolation of biologically active natural products with medical potential. In this way important drugs were discovered and developed: from the drug-veteran aspirin a hundred years ago, to penicillin about fifty years ago, and on to Taxol more recently. The latter was first isolated from the bark of the Pacific yew tree; it showed dramatic effects in cancer therapy and, therefore, induced a burst of designs for its chemical synthesis.

Modern drug design is based on the strategy of interfering with the natural function of specific proteins by small molecules of specific structure which, by virtue of their specific affinity to a protein, influence (usually inhibit) the function of that protein in vivo. In the focus of this strategy are specific supramolecular aggregates between the small molecule and the bioactive site of the corresponding protein, the occurrence and stability of such aggregates being mostly dictated by shape complementarity between the small molecule and the protein at its bioactive site.

In the second half of the last century, pharmaceutical companies invested a huge amount of money on what was then intended to become rational drug design through the use of computer assisted modeling of supramolecular aggregates between small molecules and the active sites of proteins. It was believed that with the advent of computer technology and the x-ray structure analysis of proteins the time was ripe for a major paradigm shift in pharmaceutical research: the shift from *discovering drugs by chance* to being able to *design drugs*, to design the structure of small molecules that would fit in shape and reactivity the relevant bioactive sites of proteins.

It was the dramatic, worldwide and very costly failure of this hope that eventually led to a realistic assessment of the problems of drug design. Small-molecule-protein interactions – leaving aside the question of the environment of a living cell – are for the time being still too complex a problem for the design of the chemical structure of a drug to be feasible.

It was in this period of disillusionment that a real paradigm shift in drug research emerged – combinatorial synthesis.

About a decade ago, the new strategies and technologies of combinatorial chemistry flooded the laboratories of pharmaceutical research worldwide. For centuries, the organic chemist's imperative was to work, whenever possible, with pure compounds. In drug research, the traditional empirical search for natural and synthetic drugs demanded the sequential preparation and biological testing of single molecular species. Too slow and too inefficient a strategy in a modern world of globally competing pharmaceutical companies! In the combinatorial search for drugs, whole libraries – that is to say thousands, hundreds of thousands, millions of constitutionally related but different substances, each species in necessarily minute amounts, are synthesized in one go – and the library of substances is then screened for a desired property by microanalytical methods. If a response is observed, the structure of the responding component is decoded, synthesized in bulk amounts and tested for its bioactivity. What this approach is aiming at is not to *design* a drug, but to *discover* a drug by artificially creating a huge diversity of new molecular species through the stochastic variation of reaction partners in a multistep combinatorial synthesis, followed by selection and amplification of compounds which happen to possess a desired property.

In combinatorial chemistry, the central message of evolutionary biology, *variation*, *selection* and *amplification*, finally reached the heart of chemistry. The inspiration for its development had originally come from biology, and it has changed the chemist's thinking about his own world. To be sure, in the chemist's shift from design to selection there remains a distinct ele-

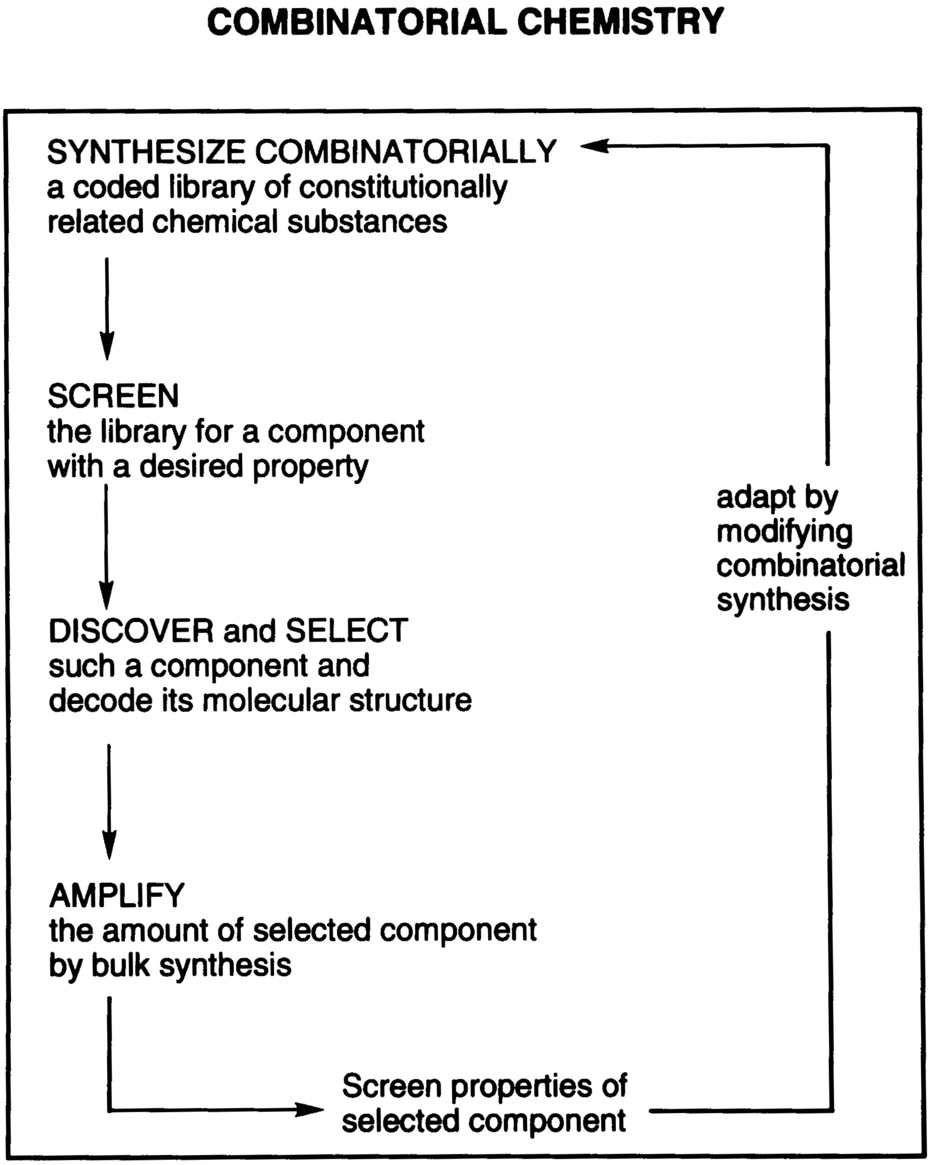
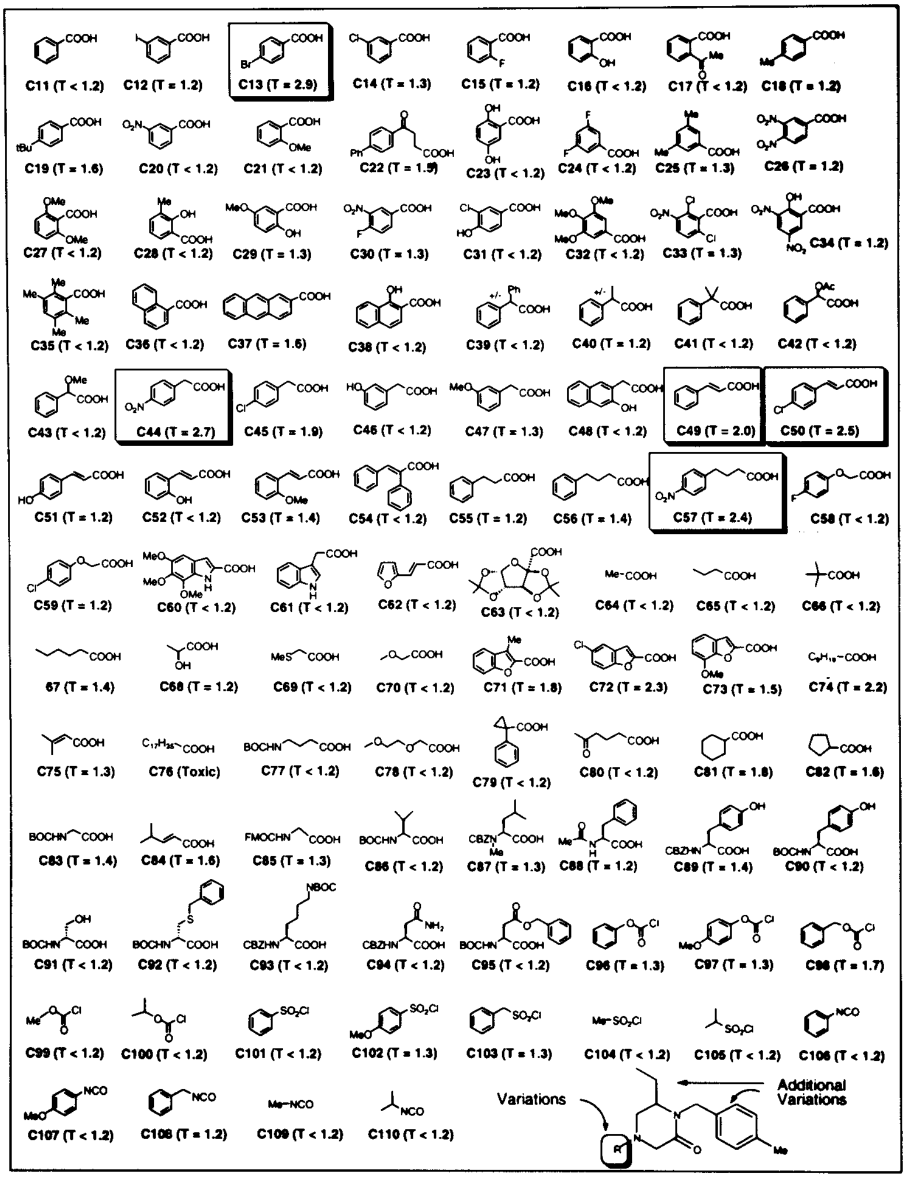


Fig. 11. Combinatorial chemistry (see also Fig. 12, p. V).



D. L. Boger, J. Goldberg, S. Satoh, S. B. Cohen, and P. K. Vogt
***Helv. Chim. Acta* 2000, *83*, 1825–1845.**

Fig. 13. Example of a library of reaction partners in a combinatorial synthesis (courtesy of Prof. D. Boger, TSRI).

ment of design – the Lamarckian element – so to say. The chemist can and does, of course, judiciously choose the structure type of the molecular diversity which he is creating for a given purpose, design libraries based on previously acquired knowledge, practicing thereby a most powerful mix of the basic strategies "design" and "selection". This mix of strategies dominates research and development in academic and industrial laboratories today. It is the modern way of searching for new drugs, new catalysts, and new materials (Fig. 14, see p. VI; Fig. 15, see p. VII).

Let us have a look at the structure of a ribosome again. The most surprising and perhaps also most important aspect discovered in this structure is the fact that in the neighborhood of the molecular machinery, where the peptide bonds are actually made, there is only RNA and no protein. The catalyst that promotes the covalent-bond chemistry of protein synthesis is an RNA, not a protein, a ribozyme, not an enzyme. This constitutes the strongest argument we have today in favor of the conjecture that an RNA world may have preceded our present DNA-RNA-protein world. In this our present world, RNA connects the genotype with the phenotype, in an RNA-world, RNA would simultaneously have fulfilled the role of both: the genotype role as a replicating nucleic acid, the phenotype role by virtue of its great diversity in sequence-specific molecular shapes. Base-sequence determines RNA's molecular shape, and the diversity of these shapes is the source of catalytic activity. "Constitution codes for conformation" is a basic tenet of chemistry.

That RNA molecules can act as catalysts is a fact, and not just a hypothesis, ever since Cech and Altmann discovered the first ribozymes about two decades ago. Great strides have been made since then in charting the landscape of the catalytic properties of RNA-molecules of varying base-sequences and of correspondingly varying molecular shapes. In vitro-evolution of catalytic RNAs, using enzymatic methods, is being pursued in a number of laboratories as one of the most powerful experimental strategies for discovering RNA's potential for catalysis.

If RNA is the alleged master molecule of an early life form that eventually evolved into ours, how did RNA originate? Was the origin of RNA the origin of life itself, as many biologists tend to think?

Nowhere will biology and chemistry ever meet in a more fundamental and more intimate way than in relation to the problem of the origins of life. This has been referred to as one of the great unsolved problems of science. In its generalized form, it is perhaps the most challenging problem of chemistry as a natural science: Can inanimate chemical matter transform itself into adaptive, evolving, and eventually living matter? The pragmatic scientist's attitude towards this question must be that it *can* and, furthermore, that it *did*. Otherwise he will not invest the effort of attempting to find out *how* it could and *how* it might have happened. Due to the pioneering theoretical studies of physical chemists such as Manfred Eigen, Ilya Prigogine and others, there are no longer any theoretical barriers against the concept of self-organization of matter towards life.

Experimental efforts will be launched in two directions: towards the creation, in the laboratory, of what may be referred to as *artificial chemical life* in order to produce a proof of principle, and towards reconstructing the natural pathways to the origins of our own life. The nature of the two approaches nicely reflects, interestingly enough, the two traditional faces of organic chemistry: the latter in the study of natural products – culminating in molecular biology – and the former in the creation of new chemical matter, culminating in the making of materials with new properties.

From a chemist's point of view, it seems quite improbable that RNA could have assembled itself prebiotically without external instruction, given the scale of the difficulties encountered in attempts to simulate experimen-

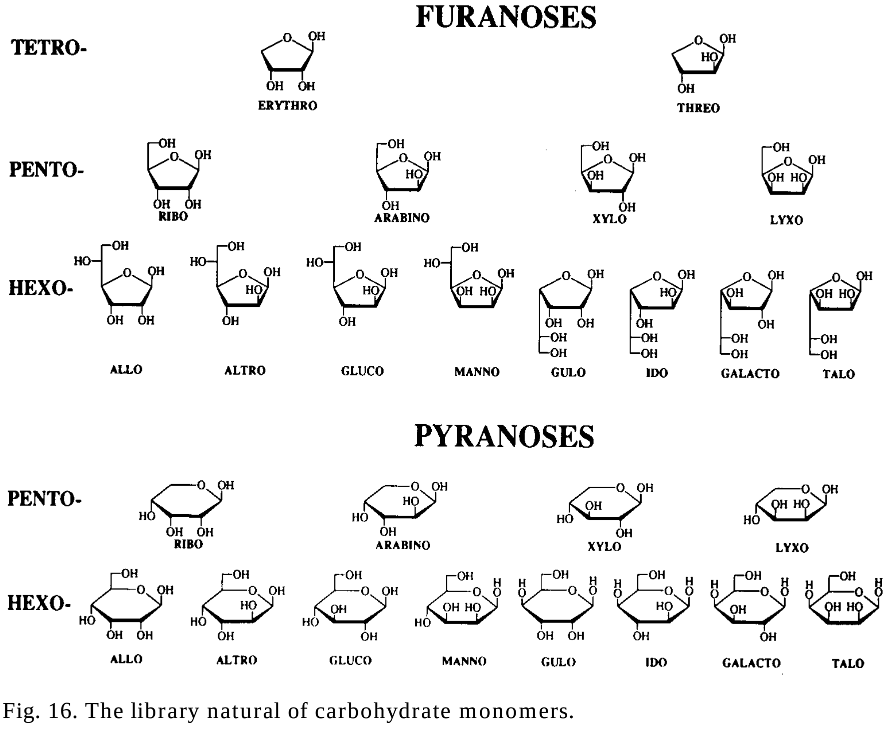


Fig. 16. The library natural of carbohydrate monomers.

tally the required steps of such a constitutional self-assembly under potentially natural conditions. One school of thought conjectures that chemical evolution started from simpler informational polymers – simpler not necessarily structurally, but with regard to accessibility – and that the evolution of such precursor systems had led to, and eventually was taken over by, RNA. The experimental search for such potential precursor systems has hardly started.

There is yet another experimental approach to the problem of the origins of RNA. It is one that focuses on function. It originates in the question: why it is that the ribofuranosyl nucleic acid system, rather than some other family of molecular structures, has been chosen by nature as the molecular basis of life's genetic system? The experimental strategy of the approach is to conceive – through chemical reasoning – potentially natural alternatives to the nucleic acid structure, to synthesize such alternatives in the laboratory by chemical methods, and to systematically compare them with the natural nucleic acids with respect to those chemical properties that are fundamental to the biological function of RNA and DNA, namely, base-pairing and replication (Figs. 17 and 18, see p. VIII).

Basic to this research is the supposition that the RNA structure originated through a process that was *combinatorial* in nature with respect to the assembly and functional selection of an informational system within the domain of sugar-based oligonucleotides; the investigation can be viewed as an attempt to mimic the selectional part of such a hypothetical process by chemical means. In principle, such studies have no bias with regard to the question of whether RNA first appeared in an abiotic or biotic environment.

Such studies have revealed that the fundamental chemical property of the natural nucleic acids, informational Watson-Crick base-pairing, is not a unique and specific property of the ribofuranosyl-oligonucleotide system. The capability is found in a surprising number of systems with an alternative backbone structure. Among them is the family of pentopyranosyl oligonucleotides, in which the pentose-sugar units have a six-membered ring, and in which each of its members show Watson-Crick pairing that is much stronger than that of RNA. Another alternative with remarkable properties is the threofuranosyl-system. Its backbone unit contains only four carbons and, therefore, it is structurally a far simpler system than RNA itself. The threofuranosyl-oligonucleotide system is at present under comprehensive study since its properties make it a candidate in the search for genetic systems that might have been ancestors of RNA.

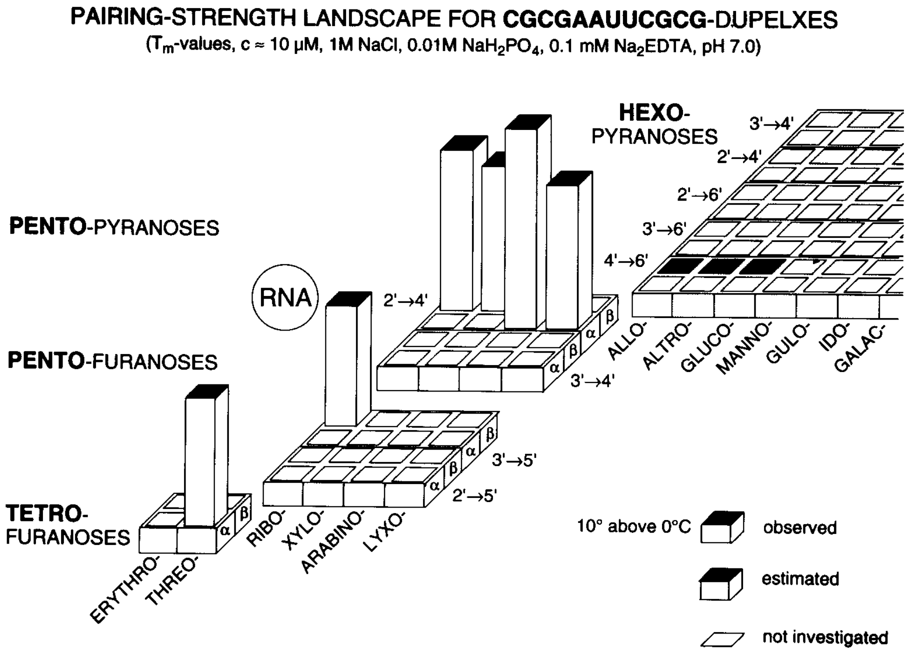
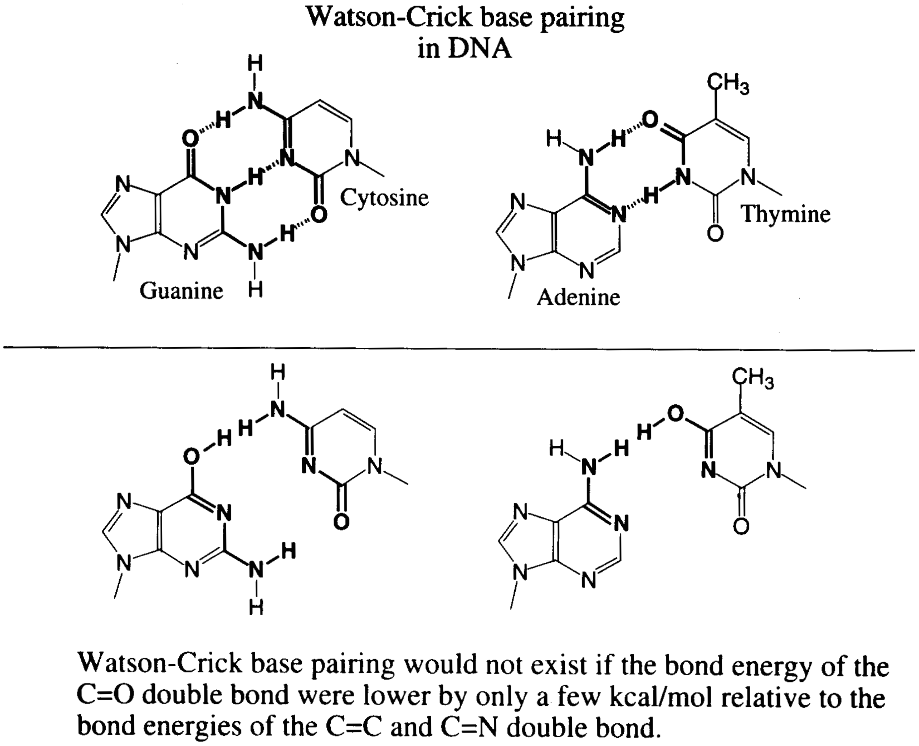


Fig. 19. Base-pairing strength landscape

Evolution – variation, selection and amplification – *can substitute for design*. This is a, if not the, central message of the Darwinian doctrine. Biologists have followed it for a long time; chemists recently adapted to it in their practical pursuits; and cosmologists are invoking evolutionary aspects in their thinking on a grand scale. The latter are confronted with the "design versus selection" dichotomy in their area in a very remarkable way. Gradually, they came to appreciate that the necessary conditions for evolution of complex life in the universe are dependent on a number of remarkable coincidences between the values of various fundamental physical constants. Our universe appears as if these constants had been tuned towards the evolution of conscious observers.

It is remarkable how the aspect of the apparent tuning of physical constants even extends into the detailistic world of chemistry; this becomes evident when one looks at the central chemical interaction in molecular biology – the Watson-Crick base-pairing.

The existence of Watson-Crick base-pairing is crucially dependent on the position of the chemical equilibrium between tautomeric forms of the nucleobases. If the average bond energy of the carbonyl double bond relative to the bond energies of the carbon-nitrogen and carbon-carbon double bond were less by only just about a few kcal per mole, the nucleobases would exist as the phenol-tautomers. Watson-Crick pairing and, therefore, the kind of life we know, would not exist.



Watson-Crick base pairing would not exist if the bond energy of the C=O double bond were lower by only a few kcal/mol relative to the bond energies of the C=C and C=N double bond.

Fig. 20. "Fine-tuning of chemical bond energies" and the existence of the Watson-Crick base-pairing

The dichotomy *"design versus selection" penetrates the whole of natural science,* and, to many, refers to aspects that go far beyond. It is this dichotomy that is underlying the creationist's crusade against Darwinism in America and elsewhere. Today, experimental chemists can experience in their work the superiority of evolutionary strategies in their searching for solutions, as compared to finding them by design. Whenever a situation such as this arises, it may be that it is the science that is not advanced enough, but more often it is the immense diversity of states, structures, patterns and relationships that overwhelms the designer and incapacitates his strategy. Basically, the experimentalist's credo is design, it is the ideal which he cannot help aiming at and striving for. . The physicist Richard Feynman is known to have written on his blackboard at Caltech: “What I cannot create, I do not understand”. Humans are said to do natural science for the sake of understanding. But do we perhaps want to understand in order to be able to make, to create? It seems fortunate that among the sciences there are some truly pure ones, like, e.g., astronomy and cosmology. The technologies which people imagine springing from them exist only in science fiction. Remarkably enough, there are scientists who ask: for how long?

CHEMICAL DESIGN OF MATERIALS

CHINTAMANI N.R. RAO

Introduction

Materials chemistry as we understand it today is of relatively recent origin. A few decades ago, the subject commonly included cement, steel and a few other topics of an applied nature. In the last two decades, the subject has emerged to be recognised as an important new direction in modern chemistry, having incorporated all the salient aspects of solid state chemistry as well. Solid state chemistry is a more formal academic subject representing the chemical counterpart of solid state physics. Materials chemistry, on the other hand, deals with structure, response and function, and has the ultimate purpose of developing novel materials or understanding structure-property relaction and phenomena related to materials. Structure and synthesis, which are integral parts of the subject, are fully utilised in the strategies for tailor-making materials with desired and controllable properties, be they electronic, magnetic, optical, dielectric, absorptive or catalytic. The material can be organic, inorganic or biological and can be in any condensed state of matter. Materials chemistry is thus a truly interdisciplinary subject incorporating the principles, systems and practice of all branches of chemistry and is based on sound foundations of physics. What distinguishes the subject from pure solid state chemistry is the ultimate materials objective.

In Table 1, we present a possible description of materials chemistry. With this description, it becomes difficult to classify materials in the way this was done in earlier years when it was common to classify them as ceramics, metals, organics and so on. We now have organic metals, superconductors and non-linear materials, as well as the ceramic counterparts. It is probably more convenient to classify materials using properties or phe-

Table 1: A Possible Description of Materials Chemistry

Constituent units	State[b]	Function	Advanced technology
atoms molecules[a] ions[a]	crystalline (molecular, ionic, polymeric, metallic etc.) non-crystalline (glasses) clusters and nanomaterials liquid crystalline	miniaturization selectivity and recognition transformation transduction transport energy storage	nanolithography microelectronics magnets, sensors and transducers photonic devices energy devices porous solids and membranes micromachines

[a] Inorganic or organic. [b] In pure monophasic form or in the form of aggregates or composites.

nomena as the bases for classification. For example, porous solids, superconductors, polymers, ferroics and composites cover all types of chemical constituents. It is, however, common to distinguish molecular solids from extended solids as they represent two limiting descriptions. Another aspect to be noted is that materials chemistry contains all the elements of modern chemistry, such as synthesis, structure, dynamics and properties. In synthesis, one employs all possible methods and conditions from high-temperature and high pressure techniques to mild solution methods (chimie douce or soft chemistry). Chemical methods generally tend to be more delicate, often yielding novel as well as metastable materials. Kinetic control rather than thermodynamic control of reactions favours the formation of such products.

All the available methods of diffraction, microscopy and spectroscopy are used for structure elucidation. For detailed structure determination, single crystals are not absolutely essential. Even powders suffice for the most part because of the advances in diffraction profile analysis. These advances in structural tools enable more meaningful correlations of structure with properties and phenomena. Catalysis is becoming more of a science partly because of our ability to unravel the structures and surfaces of catalysts. We shall examine the nature and scope of materials chemistry by briefly examining the present status of a few typical classes of materials.

What is noteworthy is the ability of chemists to design materials of choice based on their knowledge of structure and reactivity and on their unique skills in the art of synthesis.

Transition Metal Oxides

Transition metal oxides constitute the most fascinating class of materials, and exhibit a variety of structures and properties. The metal-oxygen bond can vary anywhere between highly ionic to covalent or metallic. The unusual properties of transition metal oxides are clearly due to the unique nature of the outer *d*-electrons. The phenomenal range of electronic and magnetic properties exhibited by transition metal oxides is noteworthy. Thus, the electrical resistivity of oxide materials spans the extraordinary range of 10^{-10} to 10^{20} ohm cm. We have oxides with metallic properties (e.g. RuO_2, ReO_3, $LaNiO_3$) at one end of the range and oxides with highly insulating behavior (e.g. $BaTiO_3$) at the other. There are also oxides that traverse both these regimes with change in temperature, pressure, or composition (e.g. V_2O_3, $La_{1-x}Sr_xVO_3$). Interesting electronic properties also arise from charge density waves (e.g. $K_{0.3}MoO_3$), charge-ordering (e.g. Fe_3O_4) and defect ordering (e.g. $Ca_2Mn_2O_5$, $Ca_2Fe_2O_5$). Oxides with diverse magnetic properties anywhere from ferromagnetism (e.g. CrO_2, $La_{0.5}Sr_{0.5}MnO_3$) to antiferromagnetism (e.g. NiO, $LaCrO_3$) are known. Many oxides possess switchable orientation states as in ferroelectric (e.g. $BaTiO_3$, $KNbO_3$) and ferroelastic [e.g. $Gd_2(MoO_4)_3$] materials. There is a variety of oxide bronzes showing a gamut of properties. Superconductivity in transition metal oxides has been known for some time, but the highest T_c reached was around 13 K till 1986 and we now have copper oxides with T_cs in the region of 160 K. The discovery of high T_c superconductors focused worldwide attention on the chemistry of metal oxides and at the same time revealed the inadequacy of our understanding of these materials. Recent developments related to colossal magnetoresistance (CMR) have also occurred in oxide materials ($La_{0.7}Ca_{0.3}MnO_3$).

Late in 1986 the scientific community received the big news of the discovery of a high temperature oxide superconductor. The material that was found to be superconducting with a T_c of ca 30 K was based on the cuprate La_2CuO_4. A yttrium cuprate with superconductivity above liquid nitrogen temperature emerged around March 1987. The compound was known to be $YBa_2Cu_3O_7$ (Fig. 1). Several families of cuprate superconductors have since been synthesised and characterised and the highest T_c of 135 K is found in

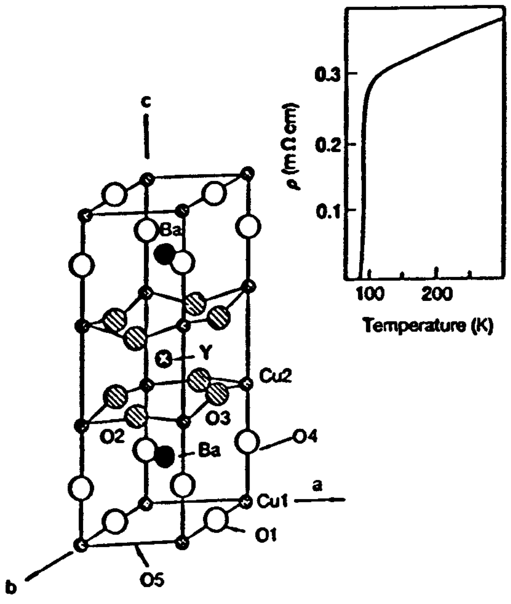


Fig. 1: Superconducting $YBa_2Cu_3O_7$.

$HgCa_2Ba_2Cu_3O_8$. Under pressure, the T_c increases to 160 K. Most of the cuprate conductors have holes as charge carriers.

Giant magnetoresistance was known to occur in bilayer and granular metallic materials. Perovskite manganates of the general formula $Ln_{1-x}A_xMnO_3$ (Ln = rare earth, A = alkaline earth) have generated wide interest because they exhibit colossal magnetoresistance (CMR). These oxides become ferromagnetic at an optimal value of x (or Mn^{4+} content) and undergo an insulator-metal (I-M) transition around the ferromagnetic T_c. These properties are attributed to double exchange associated with electron hopping from Mn^{3+} to Mn^{4+}. The double-exchange which favours itinerant electron behaviour is opposed by the Jahn-Teller distortion due to the presence of Mn^{3+}. Application of magnetic fields causes CMR around T_c (Fig. 2). The manganates show charge ordering especially when the average size of the A-site cations is small. Charge ordering also competes with double exchange and favours insulating behaviour. Thus, the manganates exhibit a variety of properties associated with spin, charge as well as orbital ordering.

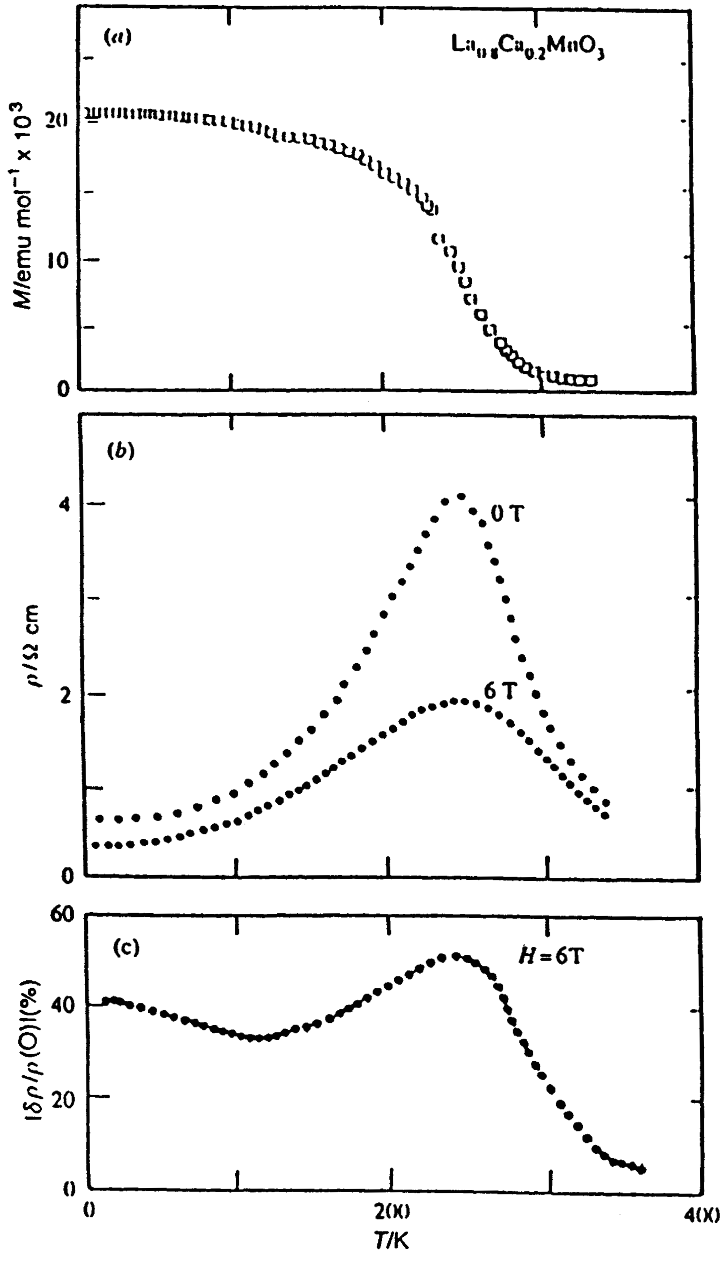


Fig. 2: Temperature-variation of (a) the magnetization, (b) the resistivity (at 0 and 6T) and (c) the magneto resistance in $La_{0.8}Ca_{0.2}MnO_3$.

Synthesis of Materials

Although rational design and synthesis have remained primary objectives of materials chemistry, we are far from achieving this goal fully. There are many instances where rational synthesis has worked (e.g., porous solids), but by and large the success is limited. Thus, one may obtain the right structure and composition, but not the properties. There are very few examples where both the structure and properties of the material obtained are exactly as desired. The synthesis of $ZrP_{2-x}V_xO_7$ solid solutions showing zero or negative thermal expansion is one such example. The synthesis of $HgBa_2Ca_2Cu_3O_8$ with the highest superconducting T_c (*ca*. 160 K under pressure) is another example. One may also cite examples of the synthesis of ionic conductors and other materials. Most inorganic materials are still discovered accidentally, the cases of high T_c cuprates and CMR manganates being well known. What is significant is the development of new strategies for synthesis, particularly those involving soft chemical routes. These methods are ideal in obtaining novel metastable materials.

The methods of soft chemistry include sol-gel, electrochemical, hydrothermal, intercalation and ion-exchange processes. Many of these methods are employed routinely for the synthesis of ceramic materials. There have been recent reviews of the electrochemical methods, intercalation reactions and the sol-gel technique. The sol-gel method has been particularly effective with wide-ranging applications in ceramics, catalysts, porous solids and composites and has given rise to fine precursor chemistry. Hydrothermal synthesis has been employed for the synthesis of oxidic materials under mild conditions and most of the porous solids and open-framework materials using organic templates are prepared hydrothermally. The advent of supramolecular chemistry has also made an impact on synthesis.

Many of the traditional methods continue to be exploited to synthesise novel materials. In the area of cuprates, the synthesis of a superconducting ladder cuprate and of carbonato- and halocuprates is noteworthy. High pressure methods have been particularly useful in the synthesis of certain cuprates and other materials. The combustion method has come of age for the synthesis of oxidic and other materials. Microwave synthesis is becoming popular while sonochemistry has begun to be exploited.

There are several reviews specific to the different families, such as layered transition metal oxides, metal phosphonates, and metal nitrides. Precursor synthesis of oxides, chalcogenides and other materials is being pursued with vigour. Thus, single-molecule precursors of chalcogenide containing compound semiconductors have been developed. Molten polychalcophosphate fluxes have been employed for the synthesis of complex metal thiophosphates and selenophosphates. Precursor carbonates are effective in the synthesis of many oxide materials. Electrochemical techniques have been useful in oxidation reactions (e.g., preparation of $SrCoO_3$, ferromagnetic $LaMnO_3$ containing ca. 30% Mn^{4+}, $La_2NiO_{4.25}$, $La_2CuO_{4+\delta}$). Intercalation and deintercalation of amines can be used to produce novel phases of oxides such as WO_3 and MoO_3. Topochemical oxidation, reduction and dehydration reactions also give rise to novel oxide phases, which cannot be prepared otherwise. Thus, $La_2Ni_2O_5$ can only be made by the reduction of $LaNiO_3$. Special mention must be made of the simple chemical technique of nebulised spray pyrolysis of solutions of organometallic precursors, to obtain epitaxial films of complex oxide materials; this technique can also be used to prepare nanoscale oxide powders. Epitaxial films of PZT, $LaMnO_3$, $LaNiO_3$ and other oxide materials have been prepared by this method.

Molecular Materials

Molecular materials, especially organic ones, have gained prominence in the last few years, with practical applications as optical and electronic materials already becoming possible. This area of research has benefited from attempts to carry out rational design based on crystal engineering and supramolecular chemistry. Polymer research has become more focused on developing new synthetic methods and controlling polymerisation. Since architecture and functionality at a molecular level control many of the properties of polymers, there are efforts to synthesise polymers with well defined topologies. Polymers involving rotaxanes, catenanes, rods, dendrimers and hyperbranched systems are some recent examples of such efforts. Recognising that hydrogen bonding is the driving force for the formation of crown ether based polyrotaxanes, mechanically linked polymers have been prepared with the possibility of molecular shuttles at polymeric level. New synthetic routes for dendrimers and hyperbranched polymers suggest many new possibilities.

Semiconducting, metallic and superconducting molecular materials have been investigated by several workers in the last two decades. New types of TTF type molecules, transition metal complexes with elongated π ligands, neutral radicals and Te-containing π donors have been synthesised and an organic superconductor with an organic anion, $\beta'' - (ET)_2SF_5CH_2CF_2SO_3$, has been discovered. Cation radical salts of BEDT-TTF and similar donors as well as BEDT-TTF salts are still a fertile ground for the production of new materials. Synthesis of linearly extended TTF analogues as well as of new TCNQ and DCNQ acceptors have been reported. The use of organic semiconductors as active layers in thin films holds promise, ∝-sexithiophene being an example. Organic polymers with a variety of electrical properties have been characterised over the years.

Molecular magnetic materials constitute an interesting area of research, although practical applications may not be feasible in the short term. Synthesis and design of molecular ferromagnets, ferrimagnets and weak ferromagnets, providing permanent magnetisation with fairly high T_c values are the main objectives of this effort. While purely organic ferromagnets have only reached modest T_cs below 2 K, materials incorporating transition metals have shown promise [e.g. $V(TCNE)_x$]. Molecular magnetic materials generally make use of free radicals such as nitroxides, high-spin metal complex magnetic clusters or a combination of radicals and metal complexes. There has been renewed interest in spin-crossover materials with emphasis on active elements for memory devices and light-induced spin changes. The study of diradicals and radical pairs has been strengthened by our understanding of how to stabilise the triplet state. C_{60}-TDAE ($T_c \approx 16$ K) and related compounds have attracted some attention (TDEA = tetrakisdimethylaminoethylene). BEDT-TTF salts with magnetic anions have been discovered. Organometallic materials based on neutral nitroxide radicals and charge-transfer (CT) complexes derived from the radicals have been examined.

High performance photonic devices have been fabricated from conjugated polynmers such as poly(*p*-phenylenevinylene), polyaniline and polythiophene. The devices include diodes, light-emitting diodes, photodiodes, field effect transistors, polymer grid triodes, light emitting electrochemical cells, optocouplers and lasers. The performance levels of many of these organic devices have reached those of the inorganic counterparts. The high photoluminescence efficiency and large cross section for stimulated emission of semiconducting polymers persist up to high concentrations (unlike dyes). By combination with InGaN, hybrid lasers can now be fabricated. Plastic electronics is moving rapidly from fundamental research to industrial applications.

The area of molecular nonlinear optics has been strengthened by investigations of three-dimensional multipolar systems, functionalised polymers as optoelectronic materials, near infrared optical parametric oscillators and related aspects. There have been some advances in chromophore design for second-order nonlinear optical materials; these include one-dimensional CT molecules, octopolar compounds and organometallics. Some of the polydiacetylenes and poly(*p*-phenylenevinylene)s appear to possess the required properties for use as third-order nonlinear optical materials for photonic switching.

Increasing interest in molecular materials has had an impact on the direction of organic chemistry as well, giving rise to large-scale activity in this area. The discovery of fullerenes and fullerene-based materials has contributed to some interesting developments. Organic-inorganic hybrids offer many interesting possibilities, with the composites exhibiting properties and phenomena not found in either component. Two types of materials can be classified, organic-inorganic units held together by weak bonds and organometallic polymers. Devices have been fabricated making use of self-organised thiols and other molecular systems. Device-related studies of functional polymers have also been fruitful. Devices and assemblies based on Langmur-Blodgett films are becoming increasingly attractive.

Porous Solids

Porous inorganic materials have many applications in catalytic and separation technologies. Zeolites have truly had a great impact on chemical industry and everyday life. The synthesis of microporous solids with connectivities and pore chemistry different from zeolitic materials has attracted considerable attention. A variety of such open framework structures, in particular Al, Zn, and Ga phosphates as well as many other metal phosphates, prepared hydrothermally in the presence of structure directing organic amines, have been characterised. In Fig. 3, we show the structure of a typical open-framework metal phosphate. There have been many break-thoughs in the design and synthesis of these molecular sieves with well defined crystalline architecture and there is a continuing quest for extra-large pore molecular sieves. Several types of new materials including tunnel and layer structures have been reported. The discovery of mesoporous silica (pore diameter 20 -200 Å) by Mobil chemists added a new dimension to the study of porous solids. The synthesis of mesoporous materials also makes use of structure-directing surfactants (cationic, anionic, and neutral) and a variety of mesoporous oxidic materials (e.g. ZrO_2, TiO_2, $AlPO_4$, aluminoborates), have been prepared and characterised.

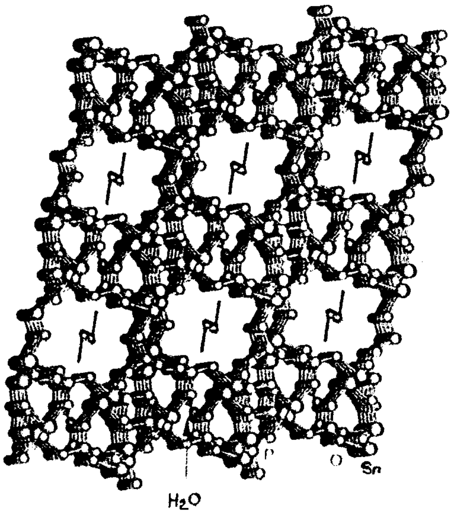


Fig. 3: Structure of a open-framework metal phosphate synthesized hydrothermally in the presence of an organic amine template.

An appropriate integration of hydrogen bond interactions at the inorganic-organic interface and the use of sol-gel and emulsion chemistry has enabled the synthesis of a large class of porous materials. Today, we have a better understanding of the structure, topology and phase transitions of mesoporous solids. Block copolymers have been used to prepare mesoporous materials with large pore sizes (>30 nm). There is also some understanding of the lamellar-hexagonal-cubic phase transitions in mesoporous oxides (Fig. 4). Derivatised mesoporous materials have been explored for potential applications in catalysis and in other areas it has been found that transition metal complexes and metal clusters encapsulated in cubic mesoporous phases show high catalytic activity for specific reactions. Macroporous solids with pore diamaters in the 200-10,000 Å range have been prepared by using polymer spheres as templates. Macroporous-mesoporous silica has been characterised.

Organic inclusion compounds and clathrates have been known for a long time. While these compounds are still being investigated, there have been efforts to synthesise novel organic or organic-inorganic hybrid structures by supramolecular means. The channels can accommodate benzene, xylenes and other molecules and the process is reversible.

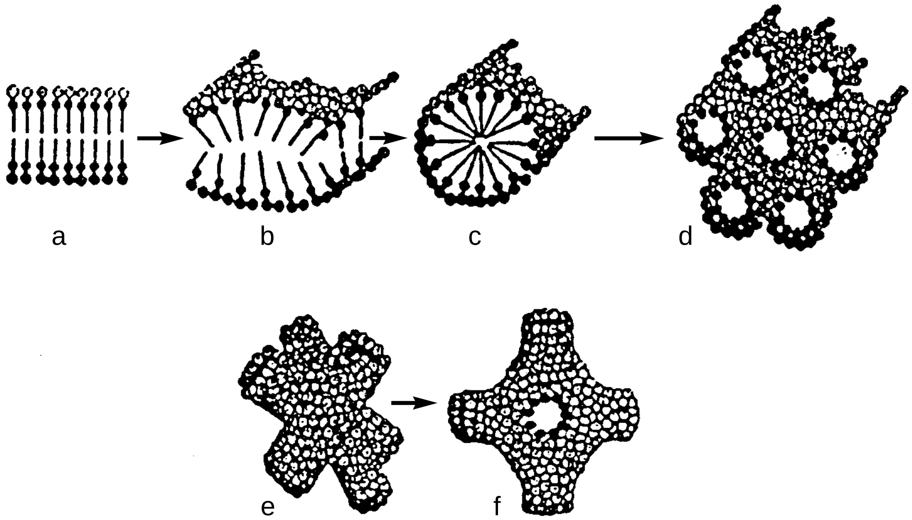


Fig. 4: Phase transitions in mesoporous solids: a-d : lamellar-hexagonal, e-f, hexagonal-cubic. The circular objects around the surfactant assemblies one metal-oxo species.

Nanomaterials

The synthesis, characterisation and properties of nanomaterials are active areas of research today. Nanostructured materials assembled by means of supramolecular organization offer many exciting possibilities. These include self-assembled monolayers and multilayers with different functionalities, intercalation in preassembled layered hosts and inorganic three-dimensional networks. Based on such materials, nanodevices and nanoelectronics seem to be on the verge of becoming realities.

The structures, electronic properties and related aspects of semiconductor nanoparticles such as CdS, InAs are of great interest. Size-dependent electronic structures of semiconductor and metal nanocrystals have been examined. The reactivity of metal clusters deposited on solid substrates varies with size. When the cluster size is small (<1 nm), an energy gap opens up. Bimetallic clusters show additive effects due to alloying and cluster size in their electronic properties. Small metal clusters of Cu, Ni and Pd show enhanced chemical reactivity with respect to CO and other molecules. Interestingly, nanoparticles of gold (non-metallic) exhibit catalytic activity.

Metal clusters and colloids, especially those with protective ligands, have been reviewed in relation to nanomaterials. Methods of preparing nanoparticles of various metals as well as nanocrystalline arrays of thiolised nanoparticles of Au, Ag and Pt have been developed. In Fig. 5, a TEM image of thiol-derivatised Au nanoparticles forming a nanocrystalline array is shown. More interestingly, by using dithiols, it has been possible to accomplish layer-by-layer deposition of dithiol-metal nanoparticle films. This is somewhat similar to the layer-by-layer self assembly of polyelectrolyte-inorganic nanoparticle sandwich films. Such superlattices involving vertical organization of arrays of metal quantum dots may have novel properties.

Intense interest has developed in carbon science ever since the discovery of the fullerenes and nanotubes properties of C_{60} and C_{70}. Synthesis and characterisation of carbon nanotubes have commanded the interest of many workers. The opening, filling, closing and functionalising of carbon nanotubes have been accomplished. Since metal particles are essential as catalysts to prepare nanotubes by the pyrolysis of hydrocarbons, organometallic precursors have been employed to generate nanotubes. Single-wall nanotubes have been obtained by the pyrolysis of metallocene

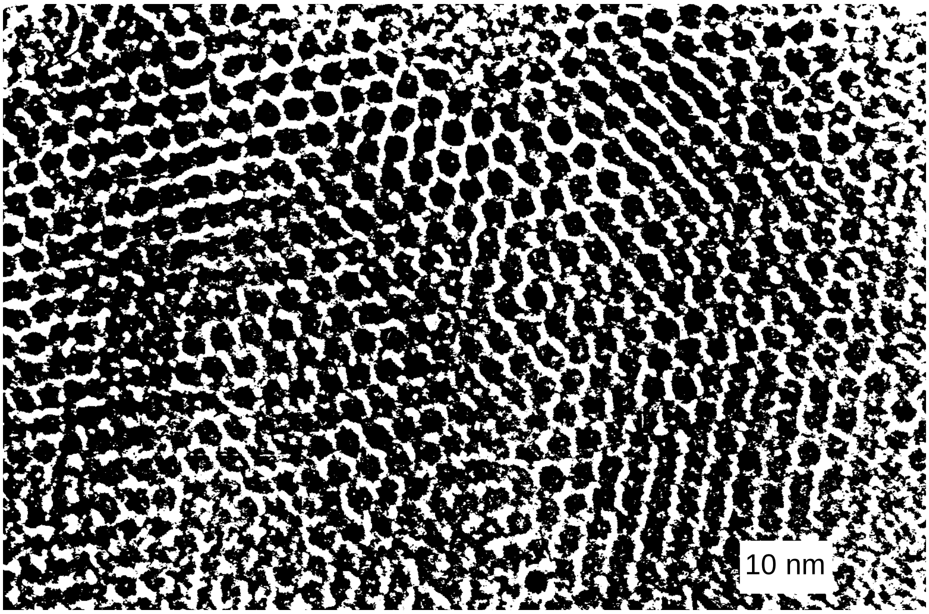


Fig. 5: Thiolised Pd_{561} nanoparticle array.

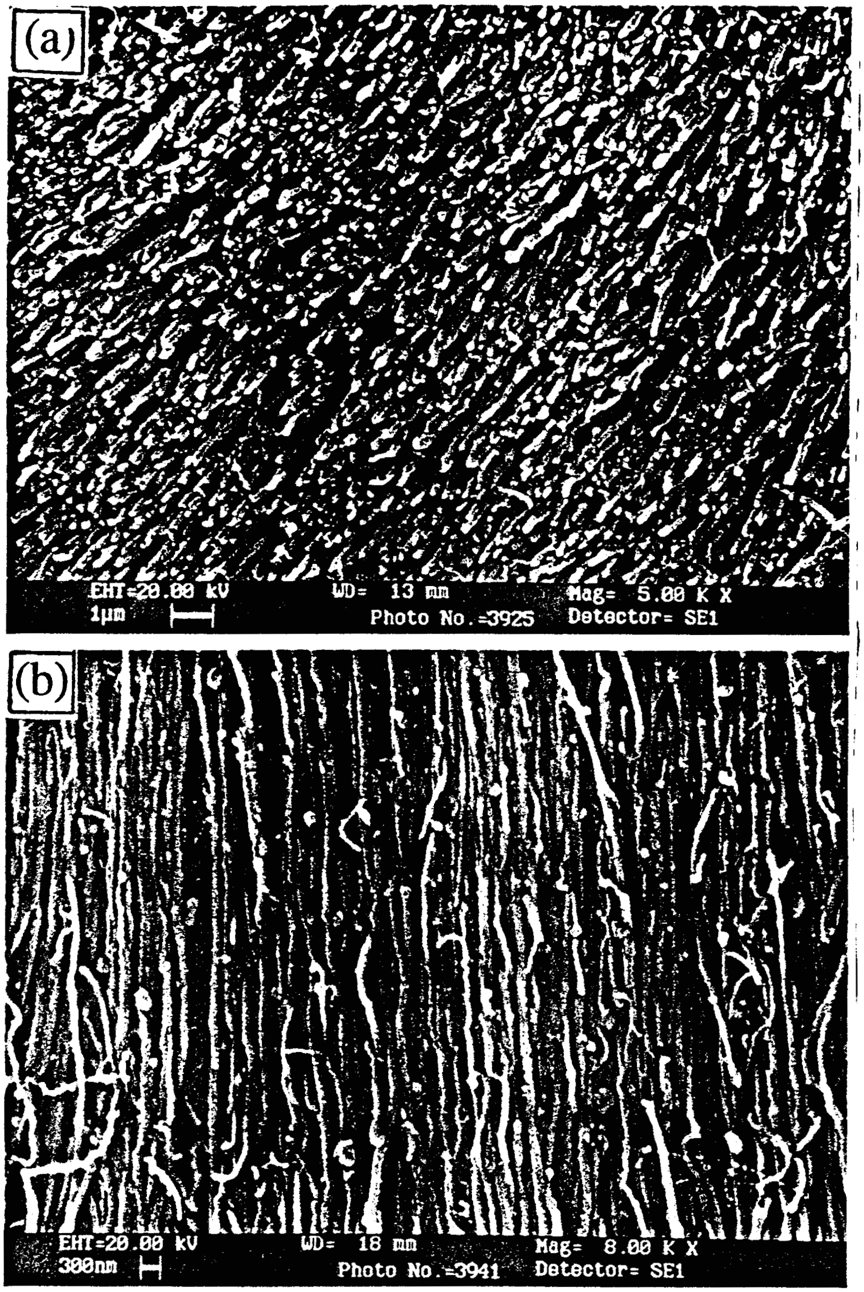


Fig. 6: Aligned carbon nanotube bundles. (a) and (b) are in two perpendicular directions.

or $Fe(CO)_5$-hydrocarbon mixtures under controlled conditions. It has also been possible to obtain copious quantities of aligned-nanotube bundles by the pyrolysis of ferrocene (Fig. 6) C-N, C-B and B-C-N nanotubes have been prepared by precursor pyrolysis as well. By using acid-treated carbon nanotubes as templates, ceramic oxide nanotubes have been prepared. Y-junction nanotubes have been prepared by precursor pyrolysis. These may be useful in nanoelectronics. The main applications of carbon nanotubes are likely to be in field-emission devices (display), hydrogen storage and as components of composite materials. Nanotubes of metal chalcogenides have been prepared and characterised.

Concluding Remarks

The above presentation should suffice to indicate the nature and potential of the chemical design of materials. Because of limitations of space, many classes of materials have not been covered. Thus, metal fluorides, nitrides and chalcogenides have not been covered here. Similarly, there is considerable development in areas of biomolecular materials as well as inorganic magnetic, non-linear, and luminiscent materials. There has been a vast amount of work on ionic conductors which has been of great value in battery development. Amorphous materials, including glasses, constitute yet another area of great interest today. Computer simulation and methods of theoretical chemistry are constantly employed to unravel the structure and properties of materials. Chemists are making use of the lessons from nature in the design of materials. Biomineralisation is one such aspect. In spite of some success in understanding the way nature designs and builds structures such as those in sea shells and diatomaceous silica, one is far from really imitating, reproducing or excelling nature.

DEVELOPMENTAL BIOLOGY: NEW TRENDS AND PROSPECTS

NICOLE M. LE DOUARIN

Developmental biology is central to all biology. It deals with the process by which the genes in the fertilised egg control cell fate in the embryo and so determine its pattern, its form, its size and much of its behaviour. The progress in developmental biology in recent years, with the application of advances in cellular and molecular biology advance, has been remarkable and a large amount of information is now available.

The mechanisms by which a fertilised egg develops into an adult can now be grasped in a way that was unimaginable a few decades ago. Yet this revolution has been a curiously silent one and many of the broader implications of our newly acquired knowledge have remained inaccessible to all but a small community of biologists. This is regrettable because the study of development provides one of the most fertile grounds for science and philosophy.

Each one of us started his or her life as a single cell of 100μm in diameter. The making of an adult from this tiny piece of living material is unique since it occurs without any information from the environmental world. Organisms are naturally endowed with a remarkable property – they make themselves.

The aim of developmental biology is to make understandable the transformation of an egg into an organism as sophisticated and as perfectly organised and adapted as a human being, a mouse, a chicken or an insect.

During embryonic development, the egg divides to give rise, in a man, to many billions of cells which form structures as complex and varied as eyes, arms, the heart and the brain. This amazing achievement raises a multitude of questions: how do the cells arising from the division of the fertilised egg become different from each other? How do they become organised into tissues and organs? What controls the behaviour of individual cells so that such highly organised patterns emerge? How are the organising principles of development embedded in the egg?

The solutions to the problem of self-making that have been proposed in the past

A commonly held scientific view during the seventeenth and eighteenth centuries was that organisms did not make themselves at all. Instead, they were thought to be already preformed in miniature within the female or male gamete. According to the theory of preformation, in the beginning there was an individual of each species of animal or plant that contained within it, as nested miniatures, all the other individuals of that species that would ever live. There were in fact two schools: the *ovists*, who believed that Eve's eggs were the repository of ourselves and of our ancestors as well as of the future of humanity; and the *animalculists* or *spermists*, who thought that we originally resided in Adam's sperm.

Attributing the original creation of encased beings to God removed most of the problem from legitimate scientific enquiry.

Although the initial creation of organisms as encased miniatures raised highly complex questions, these were solved thanks to the infinite creative powers of God. The important point was that once the miniature organisms had been created, they then developed according to the simple laws of geometry, by the enlargement of a pre-existing structure. No special forces, no complicated laws, had to be involved because all of the making had been carried out at the initial stages of creation.

At the time of Aristotle another view was countenanced to account for the development of organisms. To the view already held in ancient Greece that everything in the embryo was preformed and simply grew larger during development, this philosopher preferred the other view according to which new structures arose progressively, a process he called *epigenesis* and likened metaphorically to the 'knitting of a net'.

As the preformationists were keen to point out, this theory had the fundamental drawback that no simple physical mechanism could account for it. Epigenesis seemed to need a special 'making force', a vital force for the complicated process of the making of the organism to be achieved. Thus, at that time, the egg was considered as a blank sheet with all the information about the structure of an organism coming from the vital force that worked upon it.

The preformation/epigenesis issue was the subject of vigorous debate during the eighteenth century. But the problem could not be solved until one of the great advances in biology had taken place – the recognition that living organisms, including embryos, are composed of cells.

The cell theory changed the conception of embryonic development and heredity

The cell theory was put forward by the German botanist Mathias Schleiden [1] and the physiologist Theodor Schwann [2] between 1838 and 1839. This was one of the most illuminating advances in biology and had an enormous impact.

It was recognised that cells are the basic unit of life, that all living organisms are composed of cells which arise only by division from other cells, and that organisms arise by division of the initial cell, the egg. Multicellular organisms such as animals or plants could then be viewed as communities of cells. Development was thus recognised as being *epigenetic* since during this process many new cells are generated by division from the egg and new types of cells are formed.

A crucial step forward in understanding development was the recognition in the 1840s that the egg itself is a single cell. Next came the discovery that it arises from the fusion of two initial cells, the gametes. Work on the sea urchin and other marine organisms allowed the observation of the fusion of the two gametes, that is to say the fertilisation and, during fertilisation, the fusion, of the two nuclei. It was concluded that the nuclei were responsible for the contribution of both parents to the inherited characteristics of the offspring and therefore had to contain the physical basis of heredity.

Towards the end of the nineteenth century, chromosomes were discovered and it was found that in the zygote they are derived in equal number from the two parental nuclei. This provided a physical basis for the transmission of genetic characters according to laws developed by the Austrian botanist, the monk Gregor Mendel.

The problem of generation had two aspects which were equally important and equally difficult to account for: i) the problem of the making of the embryo and the adult from a single cell, the egg, i.e. *embryogenesis*, which involves an epigenetic process. ii) The problem of how the parental traits are transmitted to the offspring, i.e. *heredity*. Something had to be in the egg which ensured the transmission of specific and individual traits from parents to offspring. This kind of ‘memory’ had to be the repository of information about development as well.

Following the fundamental discoveries of the nineteenth century in relation to the basic unit of life, the cell, most studies were subsequently concerned with embryogenesis, and during much of the early part of the twentieth century there was little connection between embryology and genetics.

When Mendel's laws were rediscovered in 1900 there was great interest in the mechanisms of inheritance, particularly in relation to evolution, but less interest in development. Genetics was seen as the study of the transmission of hereditary elements from generation to generation; embryology was the study of how the individual organisms develop and in particular how cells in the early embryo become different from each other. Genetics in this respect seemed irrelevant to development.

However, the advances in the field of genetics led, even at that time, to a distinction between the genetic endowment of an organism, that is to say the genotype (the genetic information it acquires from his parents), and its phenotype: that is to say its visible appearance, its internal structure, its biochemistry. These terms were created by Johanssen in 1909 [3]. This raised the question of the link between the genotype and the phenotype. Genes certainly control development but environmental factors interacting with the genotype influence the phenotype. In fact, a new impetus arose from the coming together of embryology and genetics, the onset of modern *developmental biology*.

Cooperation between genetics and embryology in approaching the problems of development was a slow process.

The discovery in the early 1950s by Watson and Crick [4] of the structure of the support of heredity, the DNA molecule, and the demonstration that it can reproduce itself as such, revealed what some people called the 'secret of life' (see for example Schrödinger, 1944 [5]).

The coming together of genetics and embryology started when the modern techniques of molecular biology, and particularly gene cloning, became available. The genetic engineering revolution, which started in the early 1970s, gave a spectacular impulse to all fields of biology, including the study of embryonic development. Progress came when the nature and function of the genes were better understood. The discovery that genes encode proteins was the turning point. Since it was already clear that the proteins a cell contains determine its properties, the fundamental role of genes in development could at last be appreciated. By controlling which proteins were made in a cell, genes could control the changes in cell properties and the behaviour that occurred during development. The study of the genetic basis of development has been made possible over the last two decades by the application of the techniques of molecular biology and genetic engineering to developmental problems. At the same time, considerable progress has been made as regards the cellular aspects of development, including cell behaviour and cell to cell interactions.

How do embryos develop?

Classical embryological studies had established several fundamental principles of how developmental processes take place. When improvements to the microscope allowed the early steps of development of all kinds of organisms to be observed, von Baer systematised these observations in 1828 [6] into 'laws' and affirmed that following several rounds of divisions of the egg cell (corresponding to the phase of *segmentation*) the cells of the blastula rearrange and move to form *germ layers*: one, the *endoderm*, will line an internal cavity which becomes the gut, whereas the one that remains on the external side of the embryo forms the *ectoderm* and eventually the superficial epidermis and the nervous system. Most animals add a third, intermediate layer, the *mesoderm*, from which muscles, the heart, blood vessels, blood cells, the kidneys and most of the bones develop.

Formation of germ layers appeared as a decisive event in development since from this stage onwards the anteroposterior (AP), dorsoventral (DV) and right/left axes of the future organism became recognisable. In other words, the basic plan of the body was laid down. From that moment on, the cells of the embryo become diversified and as the organs, head, heart, tail, etc. are formed, the future organism becomes moulded through complex morphogenetic processes.

A second important notion was discovered when embryonic development started to be studied experimentally – the fact that cells interact with each other during embryogenesis.

There were two seminal experiments that demonstrated the fact that the cells, which are produced by the division of the egg, do not evolve by their own but within a community – the community of the cells that, together, construct the embryo.

Regulation in sea urchin development

This view was substantiated by the German embryologist, Hans Driesch, [7] who showed that in the early stages of sea urchin development, the blastomeres, if isolated, could give rise to normal (albeit smaller) sea urchin larvae. This was also possible with blastomeres at the 4-cell stage of sea urchin development. It showed that the nucleus of each cell at that stage was still endowed with all its ‘determinants’, that is to say, all its developmental capacities. The blastomeres were as totipotent as the egg itself. The capacity of embryonic cells to be reprogrammed is, however, not a permanent one. The embryonic territories become progressively restricted in their developmental potentialities, and, if transplanted to a different region of the embryo or explanted in vitro in a culture medium, they develop in the way that they would have developed if they had been left *in situ*, that is to say in a cell-autonomous manner, without being influenced by the surrounding embryonic cells.

These experiments also revealed that the embryo, when deprived of some of its parts, tends to develop normally by a process called ‘regulation’. Thus, if the integrity of the embryo is altered either by loss of material or by receiving an excess of it, it will, nonetheless, yield a normal adult.

The concept of regulation clearly implies that the cells interact with each other. However, the central importance of cell-cell interactions in embryogenesis was not fully established until the discovery of the phenomenon of *induction*, in which one tissue directs the development of another neighbouring tissue.

Hans Spemann and neural induction

In 1924, the German embryologist, Hans Spemann, and his young student, Hilde Mangold, [8] wanted to test the developmental capacities of various embryonic territories in the newt embryo. For this purpose, they decided to transplant parts of one embryo to another while changing their original position. In order to be able to distinguish the grafted cells from those of the recipient embryo, they chose two species of newt: one pigmented and one unpigmented. They found that a particular region of the embryo (through which the future internal germ layer was invaginating to form the endoderm – the *dorsal lip of the blastopore*, DBL) if explanted onto the ventral side of another embryo induced the formation of a second embryonic axis, with a spinal cord, head and vertebral column. Thus, the initial embryo generated Siamese twins linked together by their common digestive tract. In fact, the grafted blastoporal lip had profoundly changed the fate of the embryonic tissues surrounding it in the host embryo. These tissues were fated to become the ventral skin of the original embryo. Instead they had been induced to form dorsal structures, namely a neural plate. Hence the designation of this phenomenon as *neural induction*.

This transplantation of the DBL disturbed the dorso-ventral axis of the embryo, which became endowed with two dorsal sides. Therefore, the body plan itself was profoundly modified. Differentiation of dorsal tissues and structures in the wrong side of the embryo ensued. This meant that the body plan of the embryo is established as a scaffold, well before differentiation takes place. Thereafter, the cells differentiate and become localised along the embryonic axes according to this pre-existing plan.

One of the most important events preceding gastrulation, that is to say the formation of germ layers, is therefore the determination of the antero-posterior (AP) and of the dorso-ventral (DV) axes.

This has been understood since the time of Spemann in the first half of the twentieth century (see Viktor Hamburger 1988, for a survey [9]).

For the Amphibian egg, the favourite model of embryologists at that time, the AP axis is already established in the female gamete during oogenesis and the DV axis is determined by the point of entry of the spermatozoa.

Neither the concepts nor the technical approaches were available at that time to understand the mechanisms underlying such important events. One had to await the coming together of genetics and embryology before a model that accounts for the determination of embryonic coordinates could be provided. This was achieved for an insect – drosophila.

How do genes control the embryonic pattern along the AP and DV axes?

The work that led to this now largely accepted model was initiated by Christiane Nüsslein-Volhard and Erik Wieschaus (1980) [10]. These authors applied mutagenic agents to drosophila eggs and looked for mutations that perturbed the development of the larva.

A cascade of gene activities determines the body plan

The fruit fly *Drosophila melanogaster* had been the favourite organism of geneticists, starting with the work of Thomas Hunt Morgan in 1910. From the 1980s onwards, with the advent of gene cloning, it became the subject of extensive molecular studies.

The egg of drosophila is elongated and the main axis corresponds to the AP axis of the future larva. The larva is segmented in the same way, as the adult fly will be, with a head, three thoracic segments and six abdominal segments (Fig. 1).

Genetic analysis led to the notion that the AP axis is established during oogenesis by maternal genes that act in the ovary. The activity of these

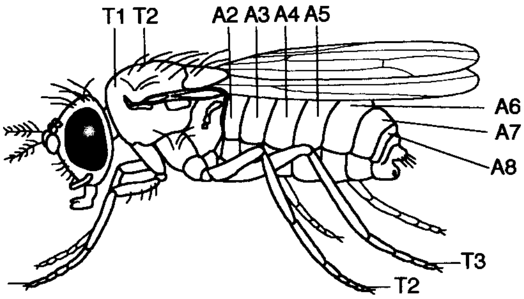


Fig. 1.

genes results in the production of proteins which, in the case of most of them, will control the activity of other genes. The products of the activity of maternal genes are deposited within the developing ovocyte.

For example, the anterior part of the fly larva is determined by a gene named *bicoid*. *Bicoid* mRNA is deposited in the anterior region of the egg. If it is mutated or destroyed by UV, the fly will not have a head. If the mRNA of *bicoid* is transplanted laterally, a head will develop in the middle of the larva.

Other genes control the development of the posterior end. Moreover, the proteins resulting from the translation of the mRNAs of maternal genes form gradients and these proteins will control the expression of zygotic genes later in development.

These zygotic genes are sequentially activated and divide the larva along the AP axis in transverse regions: large regions by *gap* genes, smaller regions by the *pair-rule* genes. The segments are then the site of patterning activities due to *segment-polarity* genes which will be responsible for determining what will be the anterior and the posterior sides of each segment. Finally, each segment will acquire its own characteristics. For example, in the thorax, each segment will have a pair of legs but only the T2 segment will carry wings, while T3 carries the balancers and the abdominal segments do not have any appendix (Fig. 1).

The latter characteristics are dependent upon the action of homeotic genes. All these genes form a network and act according to a cascade: the early expressing genes condition the expressions of the others in a defined order.

Most of the genes controlling the development of the fly have been identified. About fifty of them have been cloned and their interactions during development have been deciphered.

Homeosis and homeotic genes

The term 'homeosis' was coined by Bateson (1894) [11] at the end of the nineteenth century to refer to the process whereby, on occasions, one structure is replaced by a different one.

The homeotic genes specify the identity of each segment. Their mutations change the identity of a given segment securing its transformation into another. For example, in the mutant *bithorax*, the second thoracic segment is present twice, which means that T3 is transformed into T2 and that the fly has two pairs of wings (Fig. 2, see p. IX). Another famous homeotic mutant is called *antennapedia* because a leg instead of an antenna developed on the head.

Therefore, the normal function of homeotic genes is to specify that structures develop in the right place.

The recognition of the role of homeotic genes is due to the genetic analysis carried out by Edward Lewis [12] at the Californian Institute of Technology.

Edward Lewis discovered that the genes which control segment identity are all located on the same chromosome. The order of the genes corresponds to their order of expression along the AP axis and to the time in development when they are activated. This led him to formulate the rule of colinearity between genomic organisation and expression during development.

The discovery that all the genes that control segment identity share a common motif, the homeobox, in their organisation, was due to two groups: the group led by Walter Gehring at the Biozentrum in Basel and that led by Matthew Scott in the USA [13, 14].

Homeotic genes are present in all metazoans

By using the homeobox of *antennapedia*, Eddy De Robertis, then Professor at the Biozentrum in Basel, was able to fish out the first vertebrate homeotic gene from the frog Xenopus genome in 1984 [15].

Soon afterwards, several groups cloned homeobox containing genes from the murine, human and avian genomes. In the mouse and human species, where they have been the most studied, thirty-nine genes have been identified. They are distributed on four chromosomes. Comparison of their sequences showed that they form paralogue groups in which the genes are very similar in sequence to one of the genes of the drosophila cluster. Moreover, they are distributed along the chromosomes in the same order and their expression pattern during mouse development obeys the same colinearity rule as in drosophila.

Mutations of some genes of the clusters in the mouse resulted in abnormalities in the development of the vertebral column or of the limb and the posterior region of the head and facial bones. These abnormalities can be assimilated to homeotic transformations.

Thus, the positional identity of the different regions of the body located along the AP axis is specified by the combinatorial expression of genes of the Hox complexes, thus defining a Hox-code. Mutations or misexpression of a given *Hox* gene generally result in defects localised in the most anterior regions in which this gene is expressed, and can cause homeotic transformation.

The analogies between the *homeobox* genes of flies and vertebrates are striking and suggest that during evolution a cluster of *homeobox* genes present in an ancestor common to insects and vertebrates has been duplicated twice, thus generating the four *Hox* gene clusters now present in Vertebrates.

Some genes in each cluster have been subjected to extra-duplications and some others have been lost, but the homeobox gene clusters are part of a common mechanism established once in evolution and conserved throughout the world of metazoa to pattern the body plan. Thus, insects and vertebrates share an underlying map in their genome that directs the pattern of their body in the same relative order from head to tail.

Developmental genetics and the 'principle of connections' of Geoffroy-Saint-Hilaire

One of the most striking conclusions that can be drawn from the results so far obtained in the field of developmental genetics is that the molecular mechanisms that control embryogenesis are remarkably similar in various types of organisms. The same 'molecular modules' are used throughout the living world to fulfil either comparable or diversified functions. The novelty, in evolution, is, in the main, the result of new combinatorial arrangements of the various basic modules available.

This newly acquired knowledge is reminiscent of the 'principle of connections' proposed by the French Anatomist Geoffroy-Saint-Hilaire during the early part of the nineteenth century, when comparative anatomy was the cutting-edge of biological research and Cuvier was the most famous anatomist of his time in France.

To Cuvier, the logical principle that connected together the different parts of an organism was their functional interdependence. He applied this principle to the overall classification of animals and proposed to recognise four types of animal each organised along different lines, which he called 'embranchements': i. *vertebrates*: animals with a backbone; ii. *molluscs*: soft bodied animals such as slugs and snails; iii. *articulates*: jointed animals such as insects, and crustaceans, now called *arthropods*; iv. *radiates*: radially symmetrical animals such as starfish and jellyfish. Cuvier considered that comparisons between different animals were relevant only within embranchements, while the comparison of animals of different embranchements was meaningless.

Geoffroy-Saint-Hilaire, by contrast, thought that function was not the universal principle that underlay anatomical variations among animals in general. He thought, instead, that something universal transcended the particulars of each function, whether flying, running, swimming or holding. By comparing human and horse legs, for example, he showed that they are built according to the same plan but that their different segments vary in length. Similar variations of the forelimb from the same initial plan are seen when the human hand is compared to a bat's wing or to a whale's flipper.

Thus, in vertebrates, bones maintain the same connections in different animals, irrespective of which particular functional use they are put to.

That is what Geoffroy-Saint-Hilaire called the 'principle of connections' and what we now call *body plan* or *pattern*. Modern developmental biology supports Geoffroy-Saint-Hilaire's view and documents it at the molecular level not only for the determination of the general body plan but also for various developing systems like the limbs or the eyes, where the same genetic networks are found in drosophila and vertebrates.

The analysis of development at the cellular level

Together with the genetic analysis of development pursued on invertebrate models such as the fly *Drosophila* or the worm *Caenorhabditis elegans*, and in vertebrates, in *Zebrafish*, important advances have taken place in the last four decades in our knowledge of the cellular aspects of development. I will select two domains of this area. One relates to the problem of cell movements and cell migrations during embryogenesis, and the other deals with the early development of the mammalian embryo.

Cell migrations in the embryo

The problem of morphogenesis in itself raises several questions: how do the cells become organised in tissues and organs? What controls the behaviour of individual cells so that highly organised patterns emerge?

During embryogenesis, cells move – sheets of epithelial cells change their shape. This is particularly evident during neurulation in vertebrate embryos where one can see the neural plate becoming a groove and then a tube from which the brain and the spinal cord eventually develop. In addition to these morphogenetic movements, migrations of individual cells take place within the developing embryo and play an important role in building up tissues and organs. This role was for long unrecognised because no efficient method had been available to follow cell movements *in vivo* over periods of time that were long enough.

I devised such a method in 1969 [16] and this has since been used for the study of cell migration in avian embryos. This method is based on the observation of the particular structure of the cell nucleus in a species of bird – the Japanese quail (*Coturnix coturnix japonica*) – during the interphase. In the quail the heterochromatin is condensed in a large mass in the centre of the nucleus and associated with the nucleolar RNP. This is a rare instance in the animal kingdom which is not present in the cells of the chick – a species currently used as an experimental model in embryology. Quail and chick are closely related in taxonomy and I thought of using the possibility of distinguishing quail from chick cells because of the structure of their nucleus to devise a cell marking technique that would allow a following of the movements of embryonic cells during the whole developmental period (Fig. 3, see p. IX). Since birds and mammals are very similar as far as their embryogenesis is concerned, this method would, I thought, also permit us to obtain an insight into mammalian embryological processes, which are particularly difficult to study due to viviparity.

The rationale was to construct chimeras by substituting groups of cells from the chick embryo with their counterparts from stage-matched quails (Fig. 4). These quail cells and their progeny would keep their distinctive nuclear traits and would then remain permanently identifiable from the chick host cells whatever the duration of the association might be.

It turned out that the quail–chick chimeras developed normally and were even able to hatch, thus allowing the fate of the embryonic cells to be traced up to the adult state.

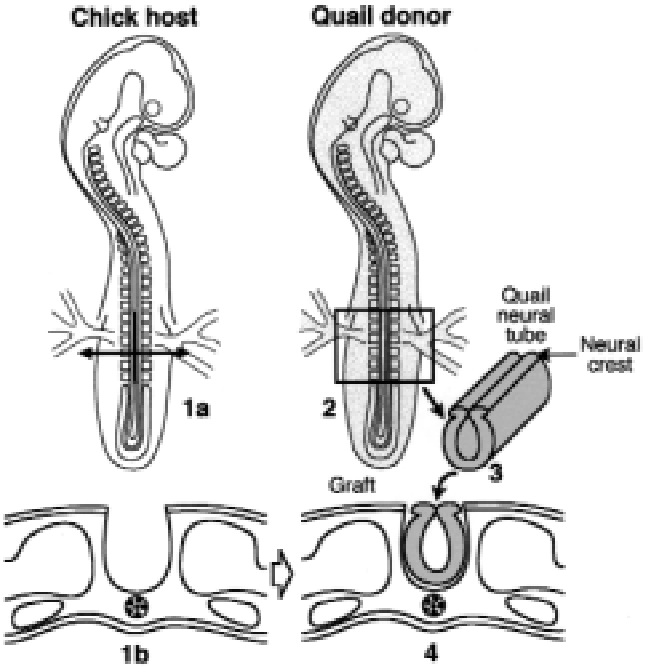


Figure 4.

This technique, which was first published in 1969, [16] was used in my laboratory to study the development of the nervous system and in particular a transitory structure of the vertebrate embryo – the neural crest (Fig 4; Fig. 5, see p. X).

My colleagues and I also took advantage of the possibility of labelling cells in the living embryo to study the cell migrations involved in the development of the immune and hematopoietic systems. The quail-chick chimeras were also widely used in other laboratories to investigate a number of problems connected with cell migration and differentiation.

The information on the advances resulting from the use of this technique are available in articles that have been devoted to the neural crest [17-19].

Mammalian embryology: recent advances open up new avenues in therapy

Another field which has witnessed spectacular advances during the last decades is mammalian embryology. Culture conditions were devised in the

1950s that allowed *in vitro* fertilisation of the mouse egg. Embryos can develop outside the maternal womb up to the blastocyst stage and if at that point they are introduced into the uterus of a foster mother their development can proceed normally.

The success of *in vitro* fertilisation in the mouse prompted Robert Edwards and Patrick Steptoe in England to extend this technique to humans. In 1969, Edwards reported in the journal *Nature* [20] that they had succeeded in obtaining in vitro fertilisation of a human egg and in culturing the embryo up to the blastocyst stage. The road was then open to *in vitro* fertilisation in humans, and in 1972, Louise Brown, the first baby to start development on the bench of a laboratory, was born.

A better knowledge of the early stages of the development of the mammalian egg could be obtained from the embryos that developed *in vitro* and were thus accessible to experimentation. It was shown that, like those of the sea urchin or the frog, the mammalian embryo may display a large measure of plasticity. It is possible to remove one or two cells from the embryo at the morula stage without impairing its further development. One can fuse two morulas or add cells into a blastocyst and still obtain a normal mouse.

The possibility that the embryo can regulate its development after the removal of some cells was also found to hold for the human egg. This observation made possible the prenatal diagnosis of certain genetic abnormalities.

Another important observation resulting from basic research on the early stages of mammalian development led to the culture of *embryonic stem cells*. Early on in mammalian embryogenesis the cells become divided into two sets: the external layer becomes irreversibly fated to yield the placenta while the embryo develops exclusively from the inner mass of cells that are present within the blastocyst (Fig. 6).

In 1981 it was found that if the inner cell mass is withdrawn from the blastocyst and cultured *in vitro* in certain conditions, it does not yield the various differentiated cell types that appear in the embryo. The component cells can be maintained in an undifferentiated state while continuing to proliferate actively [21, 22]. Appropriate culture conditions, including definite growth factors, are required to prevent these embryonic cells from differentiating and thus to maintain them in a pluripotent state. These cells are termed ‘Embryonic Stem Cells’ (ES cells), meaning that, while actively dividing, they retain the developmental capacities of the egg itself and of the early cells arising from its segmentation.

This discovery was important in several respects. Firstly, it provided biologists with large numbers of embryonic cells with which they could study

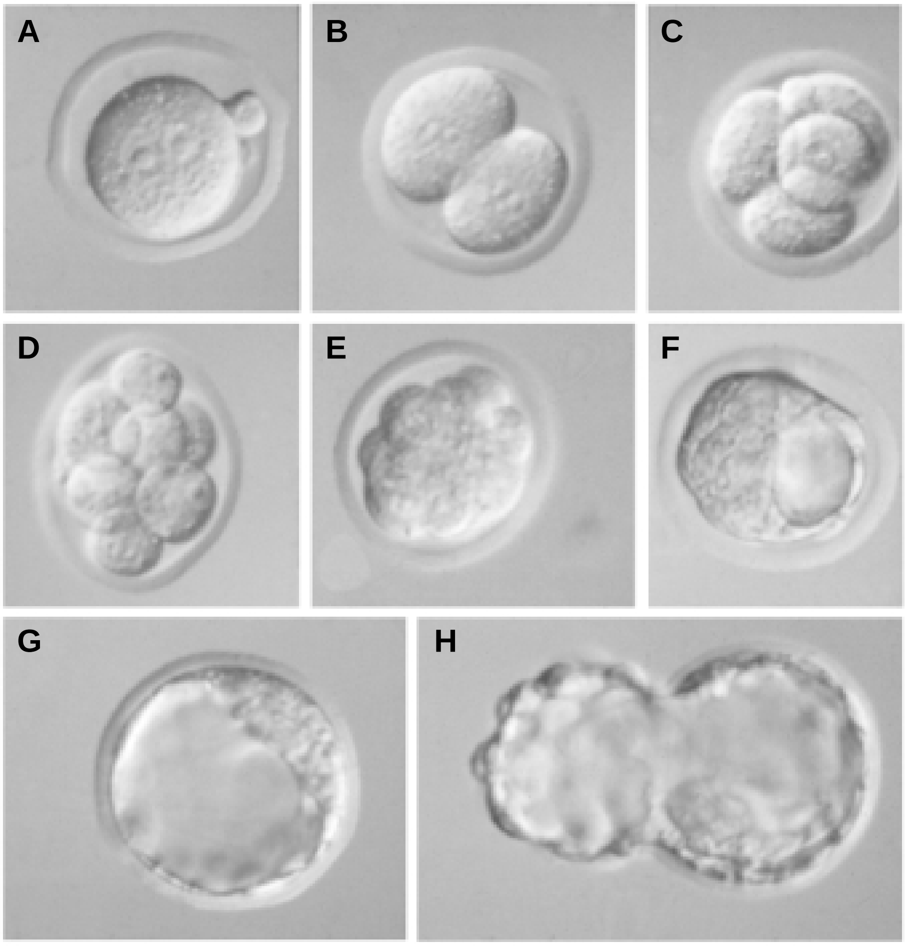


Fig. 6.

the central problem of how the cells of the developing organism can diversify, even though they possess the same genome. Secondly, with appropriate cytokines, these cells can be induced to differentiate into nearly any type of cells composing the body: neurones, glia, muscle, blood, bone, cartilage, etc.

This suggested that these cells could be used to cure degenerative diseases. The ability to obtain cells of different kinds which are fully functional, in a potentially unlimited amount, is evidently an important prospect for cell therapy. It opens up new possibilities by which to cure diseases caused by the deficiency of selective cell types and marks the onset *regenerative* medicine.

Recently, ES cells have been successfully derived from human embryos and the prospects that such methodologies could be applied to humans are now in view. However, the utilisation of human embryos for such purposes raises ethical issues that have to be carefully considered before these techniques are implemented.

The considerable progress that has been achieved over the last decades in molecular and cellular developmental biology has revealed another possibility for cell therapy. It has been discovered that the cells which in every adult differentiated tissue maintain cellular homeostasy have wider differentiating capabilities than was previously assumed. These tissue-specific stem cells had been the subject of intensive research and their potentialities were considered to be restricted to the tissue type to which they belonged. For instance, the hemopoietic stem cells or the satellite cells of the muscle were known to produce blood cells and myocytes respectively. In fact, with the use of appropriate culture conditions and growth factors, most tissue specific stem cells (including neural stem cells of the adult brain) have been found to be able to yield many other cell types. Even if these adult stem cells may not be as pluripotent as ES cells, it is clear that they might provide a more generally acceptable alternative source for cell therapy. It has to be underlined that active research is necessary, both on animal and human cells, to evaluate properly the real potential of these various methods in the treatment of degenerative diseases.

REFERENCES

[1] Schleiden, M. (1838). *Beiträge zur Phylogenesis* (Müller's Archiv).

[2] Schwann, T. (1839). *Mikroslopische Untersuchungen über die Übereinstimmung in der Struktur und dem Wachstum der Tiere und Plfanzen* (Berlin).

[3] Johanssen, W. (1909). *Elemente der exakten Erblischkeislehre* (Jena: Gustav Fischer).

[4] Watson, J.D. and Crick, F.M.C. (1953). 'Molecular structure of nucleic acids. A structure for desoxyribose nucleic acid', *Nature*,171, 737 -738.

[5] Schrödinger, E. (1944). *What is Life?* (Cambridge: Cambridge University Press).

[6] von Baer, K.E. (1828). *Ueber Entwicklungsgeschichte der Tier. Beobachtung une Reflexion*. (Reprinted 1967 by Culture et Civilisation, Bruxelles), K.E. von Baer ed., (Königsberg: Gebrüder Bornträger).

[7] Driesch, H. (1891). 'Entwicklungsmechanische Studien I. Der Wert der beiden ersten Furchungszellen in der Echinodermenentwicklung. Experimentelle Erzeugung von Teil- und Doppelbildungen', *Zeitschr. wiss. Zool.*, 53, 160-183.

[8] Spemann, H. and Mangold, H. (1924). 'Uber Induktion von Embryonalanlagen durch Implantation artfremder Organisatoren', *Rou'x Arch. f. Entw. Mech.* 100, 599-638.

[9] Hamburger, V. (1988). *The Heritage of Experimental Embryology. Hans Spemann and the Organizer* (Oxford: Oxford University Press).

[10] Nüsslein-Volhard, C. and Wieschaus, E. (1980). 'Mutations affecting segment number and polarity in *Drosophila*'. *Nature*, 287, 795-801.

[11] Bateson, W. (1894). *Materials for the Study of VariationTreated within Regard of Discontinuity in the Origin of Species*, W. Bateson, ed. (London: MacMillan).

[12] Lewis, E.B. (1978). 'A gene complex controlling segmentation in Drosophila', *Nature*, 276, 565-570.

[13] McGinnis, W., Garber, R.L., Wirz, J., Kuroiwa, A. and Gehring, W.J. (1984). 'A homologous protein-coding sequence in Drosophila homeotic genes and its conservation in other metazoans', *Cell*, 37, 403-408.

[14] Scott, M.P. and Weiner, A.J. (1984). 'Structural relationships among genes that control development: sequence homology between the Antennapedia, Ultrabithorax, and fushi tarazu loci of Drosophila', *Proc. Natl. Acad. Sci. USA*, 81, 4115-4119.

[15] Carrasco, A.E., McGinnis, W., Gehring, W.J. and De Robertis, E.M. (1984). 'Cloning of an *X. laevis* gene expressed during early embryogenesis coding for a peptide region homologous to *Drosophila* homeotic genes', *Cell*, 37, 409-414.

[16] Le Douarin, N. (1969). 'Particularités du noyau interphasique chez la Caille japonaise (*Coturnix coturnix japonica*). Utilisation de ces particularités comme "marquage biologique" dans les recherches sur les interactions tissulaires et les migrations cellulaires au cours de l'ontogenèse'. *Bull. Biol. Fr. Belg.*, 103, 435-452.

[17] Le Douarin, N.M. (1982). *The Neural Crest* (Cambridge: Cambridge University Press).

[18] Le Douarin, N.M. and Kalcheim, C. (1999). *The Neural Crest* (second edition, New York: Cambridge University Press).

[19] Le Douarin, N.M. (2000). *Des chimères, des clones et des gènes* (Paris: Odile Jacob Sciences).

[20] Edwards, R.G., Bavister, B.D. and Steptoe, P.C. (1969). 'Early stages of fertilization in vitro of human oocytes matured in vitro', *Nature*, 221, 632-635.

[21] Martin, G.R. (1981). 'Isolation of a pluripotent cell line from early mouse embryos cultured in medium conditioned by teratocarcinoma stem cells', *Proc. Natl. Acad. Sci. USA*, 78, 7634-7638.

[22] Evans, M.J. and Kaufman, M.H. (1981). 'Establishment in culture of pluripotential cells from mouse embryos', *Nature*, 292, 154-156.

ERREUR, CORRECTION, RÉHABILITATION ET PARDON

GEORGES COTTIER, O.P.

1. Lors de la “Journée du Pardon” célébrée le 12 mars 2000, dans la prière universelle, une des confessions portait sur les fautes commises dans le service de la vérité. Elle se rapportait à des hommes d’Eglise qui, pour répondre au devoir de défendre la vérité, ont eu recours à des méthodes non évangéliques et d’intolérance. La prière énonçait le “ferme propos de chercher et de promouvoir la vérité dans la douceur de la charité, sachant bien que la vérité ne s’impose qu’en vertu de la vérité elle-même”.

Cette confession et cette prière sollicitent notre réflexion sur deux thèmes: celui de la défense de la vérité; le problème est d’ordre éthique, il porte sur la moralité des moyens. Le second concerne l’autorité de la vérité, je veux dire l’autorité intrinsèque à la vérité comme telle. Celle-ci ne s’impose que par elle-même. On pourrait évoquer ici la formule de Spinoza: *verum index sui et falsi*, mais dans un sens qui n’est pas celui de Spinoza, lequel présupposait que notre raison avait accès à l’évidence directe de la vérité, sans avoir besoin de recourir à la médiation de l’argumentation ou de la vérification expérimentale.

Je vous propose quelques brèves réflexion sur l’un et l’autre thème.

2. L’idée de défense de la vérité touche l’éthique de la connaissance ainsi que celle de la communication de la vérité. Mais cette idée se rencontre, antérieurement à la référence éthique, en vertu de la nature complexe de la connaissance humaine. Spinoza lui-même, que j’ai évoqué à titre de comparaison, nous donne la preuve que son adage *verum index sui et falsi* représente pour lui plus un idéal qu’une traduction exacte de la manière humaine de connaître, en tant que lui aussi doit proposer des démonstrations et des réfutations. S’il en est ainsi c’est parce que l’accès à la vérité n’est pas

pour nous immédiat. Notre connaissance a son point de départ dans les sens; elle est discursive; le questionnement suppose une relative ignorance, de sorte que notre savoir est le fruit de la recherche; celle-ci doit vaincre des obstacles et des difficultés, elle est sujette à l'erreur. De là les discussions, les objections, les réfutations, nécessaires aux progrès du savoir. La défense de la vérité est le moteur du débat intellectuel, comme mise à l'épreuve nécessaire de la vérité des idées. Mais, à ce niveau qui est essentiel, la défense de la vérité s'appuie sur les moyens intrinsèques à la raison elle-même. Le problème éthique peut déjà se poser ici, pour autant que des incorrections volontaires interviennent dans les raisonnements ou dans les expérimentations. D'ailleurs parallèlement à la logique, les Grecs s'intéressaient également aux arguments des sophistes, considérés comme des techniques élaborées en vue de tromper.

3. La considération éthique intervient quand la défense de la vérité s'appuie non plus sur les ressources propres de la raison, qui sont homogènes à la vérité elle-même, telles que sont les règles de la logique et de la méthode, mais sur des facteurs extrinsèques au processus de la recherche de la vérité.

Autrement dit, le problème se pose dès lors qu'intervient une autorité d'un autre ordre que celui de la connexion des idées qui s'imposent par leur propre évidence.

Cette autorité est-elle légitime? Et si oui, d'où tient-elle cette légitimité?

La question est d'une importance décisive. Les réponses possibles peuvent se réclamer de diverses considérations. Notons d'abord que la défense de la vérité peut s'entendre négativement comme condamnation de l'erreur qui s'y oppose. Ceci dit, l'autorité extérieure intervient parce que la divulgation d'une idée ou d'un savoir apparaît comme nocive à des intérêts, qui peuvent être des intérêts réels ou des intérêts usurpés. L'autorité politique peut interdire la divulgation des résultats d'une certaine recherche pour des raisons militaires, à supposer que celles-ci soient justifiées. Un pouvoir tyranique (et ici il faut parler de pouvoir plutôt que d'autorité) interdit la propagation de certaines idées où il voit une menace. Mais une autorité, pensons ici à une autorité religieuse, peut intervenir en se réclamant elle-même d'une vérité qu'elle connaît par ailleurs. Nous reviendrons sur ce dernier cas.

D'une manière générale, les droits de l'homme, reconnus et appliqués, et notamment le droit à la liberté de pensée, le droit à la liberté de conscience, le droit à la liberté religieuse devraient offrir une garantie efficace contre de possibles abus ou déviations.

Je ne fais qu'évoquer ici un vaste champ de problèmes, qui mériteraient à eux seuls d'être longuement développés.

4. Pour pouvoir poursuivre notre réflexion, il convient de proposer quelques points de repère épistémologiques. Je les énonce, sans apporter ici leur justification.

a. Nos connaissances ne sont pas univoques, au sens où elles ressortiraient à un unique type de savoir. Comme le réel à connaître est intrinsèquement différencié, les approches de ce réel diffèrent entre elles par le point de vue, par les questions posées, par la méthode adoptée, par les moyens utilisés. Ajoutons aussitôt que c'est toujours la même raison qui est à l'oeuvre dans les divers champs du savoir. L'approche mathématique, l'approche expérimentale, ou l'approche philosophique ne sont pas réductibles à une unique forme de savoir, bien que des contacts et des influences réciproques existent entre ces diverses approches.

b. Toutes les disciplines du savoir ne peuvent pas prétendre à un même degrè de certitude. En certains domaines, on doit se contenter de probabilités, plus ou moins fortes. La portée des lois énoncées reflètera ces différences.

Des disciplines comme l'histoire ou la sociologie, par leur nature même, comportent une dimension d'interprétation. Elles font appel à des attitudes comme l'empathie et développent des méthodes de contrôle qui permettent d'éviter que l'implication du sujet ne se transforme en subjectivisme.

Le jugement pratique qui guide immédiatement le libre choix à la lumière de la loi morale, met en évidence une autre forme d'implication de la subjectivité du sujet dans l'élaboration du jugement lui-même.

Les cas évoqués jusqu'ici se situent au niveau de la raison s'appuyant sur ses propres ressources. Il faut dire quelque chose maintenant de la Révélation et de la structure de la foi qui y correspond.

Il s'agit évidemment d'une problématique qui concerne avant tout les croyants, mais qu'il convient de connaître à cause de l'incidence des croyances religieuses sur les grandes cultures mondiales. Je parle ici de la foi chrétienne.

Pour ce qui nous concerne, disons que l'idée de Révélation présuppose que la raison humaine, à côté de cette source du connaître qu'est sa propre lumière, est ouverte à une autre source, supérieure, – la Révélation – qui est due à une intervention illuminatrice de la Transcendance, laquelle permet l'accès à des vérités décisives sur elle-même et sur les voies du salut. Dieu nous parle par l'intermédiaire de témoins, comme les prophètes et par Celui qui est le témoin par excellence, le Christ, qui nous transmettent des vérités que nous ne pouvons pas voir par nous-mêmes, et qu'en conséquence nous croyons.

Croire, en effet, c'est accueillir une vérité qu'on ne peut pas directement vérifier soi-même, mais qui est reçue sur l'autorité du témoin. Ce que l'on peut et doit vérifier c'est la crédibilité du témoin. La certitude de foi s'appuye sur l'évidence possédée par un autre, c'est-à-dire par le Témoin. c'est pourquoi l'autorité (du témoin) est à la base de l'adhésion de foi; on parle dans ce sens de l'obéissance de la foi. Le contenu de la Révélation ou message de la foi dépasse les capacités naturelles de notre raison. Le croyant se remet soi-même au Témoin accrédité par Dieu; la foi comporte ainsi une dimension de confiance.

c. Pour la foi catholique, cette Révélation est confiée à l'Eglise. C'est par la médiation de l'Eglise, que le croyant singulier y a accès. L'Eglise elle-même conserve, transmet et explicite le message de la Révélation par l'organe du Magistère. A des degrès divers selon la gravité de l'enjeu, le Magistère peut compter sur les lumières de l'Esprit Saint, qui l'assiste.

La tradition chrétienne a dès le début pris conscience du fait que l'adhésion de foi n'est pas une adhésion aveugle. On connaît la double formule d'Augustin: *Credo ut intelligam*, *intellego ut credam*.

La foi chez le croyant suscite la pensée et la réflexion; rationnellement organisée, cette réflexion constitue la théologie. Celle-ci est donc l'organisation raisonnée du contenu de la foi, de ses prolongements et de ses conséquences.

Au niveau des principes, où nous nous situons jusqu'ici, quelques points doivent être soulignés.

1. Dieu étant la source de toute vérité, il ne peut *de droit* y avoir opposition entre la lumière naturelle de la raison et la Révélation.

2. La conséquence directe de cette harmonie de principe est que le théologien pour pénétrer l'intelligence de la foi a besoin de l'instrument philosophique, et aussi doit intégrer dans sa vision l'apport des diverses disciplines du savoir.

3. L'unification du savoir est une exigence de la pensée. Cette exigence

est présente déjà chez des Pères de l'Eglise comme Augustin. Elle est à la base des grandes *Sommes* médiévales.

Mais ici il importe d'apporter une double précision.

4. L'unité du savoir n'est pas une uniformisation, au sens des systèmes encyclopédiques. Elle présuppose au contraire que chaque discipline scientifique soit respectée dans sa spécificité, c'est-à-dire dans son objet propre, dans la méthode qui lui est adaptée et dans le type de vérité à laquelle elle parvient. Il s'agit en d'autres termes d'une unité organique, qui requiert une grande conscience épistémologique. Celle-ci permettra d'éviter les extrapolations indues et l'empiétement d'une discipline dans le champ d'une autre.

d. Ici se situent les difficultés que l'exercice des sciences peut rencontrer du côté de la théologie, et, a fortiori, du Magistère de l'Eglise.

Il est significatif à ce propos qu'un mot comme celui de *dogme* ainsi que l'adjectif *dogmatique*, qui appartiennent au langage de la foi et de la théologie soient devenus des termes péjoratifs quand ils sont appliqués aux recherches de la philosophie ou des sciences.

D'où vient ce renversement sémantique? Il vient de tragiques malentendus épistémologiques. La liberté de pensée, par quoi on entend l'absence de préjugés ou de préconceptions et la liberté du questionnement, est une condition de l'exercice de la science. Cette liberté de pensée n'ignore pas la dimension éthique, en ce qui concerne soit la déontologie du scientifique soit des exigences qui découlent du sujet d'étude, notamment si ce sujet est l'homme. Ce n'est pas cet aspect qui me retient pour l'instant, bien qu'il soit d'une importance majeure. Ce que j'entends souligner c'est la différence entre l'exercice des sciences et celui de la théologie, différence qui tient ici et là à la structure épistémologique. La théologie, en effet, se réfère à l'autorité de la Parole de Dieu, Parole qui lui est donnée et qu'elle est appelée à interpréter et à scruter. Ainsi une autorité fait partie de l'objet même de la théologie, ce qui ne veut pas dire que les théologiens ne disposent pas d'une certaine liberté de recherche en consonance avec leur objet. Mais projeter sur la recherche scientifique des critères qui sont propres au savoir théologique est un abus qui ne peut que paralyser leur exercice. Il semble alors que la théologie entende dicter à la recherche scientifique le résultat qu'elle doit atteindre. Cette intrusion, qui n'est pas justifiée, est à distinguer d'une interpellation réciproque.

5. Revenons à l'exigence d'unité du savoir.

La Révélation elle-même l'appelle en vertu de concepts comme celui de *création* ou de *salut*, désignant par là les finalités de l'histoire humaine et, à travers l'homme, de la nature entière. Cette exigence d'unité et d'universalité est reprise par l'enseignement du Magistère. Elle est rejointe par l'effort d'intégration des connaissances qui a marqué les *Sommes* médiévales qui unifient l'ensemble des savoirs sous l'égide de la théologie.

Si nous regardons au contenu de ces Sommes, nous voyons aussitôt qu'elles contiennent des strates de nature différente. Je n'entends pas par là uniquement la convergence d'une pluralité de savoirs, mais plutôt et surtout le rapport de ces savoirs au temps.

Je m'explique sur ce point, qui me paraît décisif.

Il ne suffit pas de dire que l'oeuvre d'un théologien comme toute oeuvre de l'esprit humain est conditionnée par son époque et en porte la marque. La culture n'est pas une pure prospection archéologique. Si nous interrogeons les oeuvres du passé, c'est parce qu'à travers la mémoire culturelle elles nous transmettent un message qui n'a pas perdu de son actualité. Mais précisément tous les éléments que contiennent ces oeuvres, n'ont pas la même force d'actualité. Autrement dit, dans l'héritage du passé certains ont valeur permanente, d'autres sont définitivements caducs, d'autres problématiques. Ainsi l'oeuvre de Thomas d'Aquin contient, à côté d'illustrations de vérités de foi et l'élucidation de principes métaphysiques, dont la vigueur n'a pas décliné, de larges emprunts à la science aristotélicienne, qui ont perdu toute pertinence.

De telles oeuvres, étant oeuvres de la raison, possèdent certes une forte architecture, mais, à regarder les parties, toutes n'ont pas le même rapport à l'égard de l'usure du temps. Ces clivages ne sont pas perçus par les contemporains qui au contraire s'arrêtent à l'homogénéité des parties, homogénéité qui en réalité n'existe pas, comme nous le voyons grâce au recul du temps.

C'est que la raison, là où il ne s'agit pas de recevoir une Parole qui est donnée ou de remonter aux intuitions fondatrices de la métaphysique, est discours; elle progresse, et ce progrès comporte un processus constant de remise en cause et de rectification. En ce sens, les visions du monde changent avec le temps.

Le drame de Galilée, dont les travaux de notre Accadémie ont contribuée à dégager la signification et à tirer la leçon qui s'impose pour l'avenir, est éclairant à ce propos.

Pendant des siècles, les théologiens, et, plus largement, la culture chrétienne ont tenu comme faisant partie de l'enseignement révélé une vision du monde qui en fait ne lui appartenait pas. C'est cette vision du monde qui s'est trouvée bousculée par l'approche nouvelle de Galilée. L'innovation, telle fut la crainte du Magistère et des théologiens qui le conseillaient, n'allait-elle pas faire vaciller l'édifice entier de la foi? On ne peut méconnaître la gravité de la question. Ce qui a manqué alors ce fut un théologien de génie, qui, symmétriquement aux découvertes de Galilée, eût ouvert la voie à une interprétation plus rigoureuse de l'Ecriture. La lettre de Galilée à la Grande-Duchesse de Toscane, Christine de Lorraine (1615) avait pourtant ouvert la voie. Seul Robert Bellarmin avait entrevu le problème et son enjeu.

Depuis cette époque, et sans doute sous la poussée d'événements, auxquels le procès de Galilée n'est pas étranger, de grands pas en avant ont été faits notamment dans les disciplines de lecture de l'Ecriture. *Dei Verbum* de Vatican II en est un témoin particulièrement important.

Nous pouvons tirer une première conclusion de nos réflexions. Si l'exigence d'unification des savoirs correspond à une exigence incoercible de l'esprit, cette unification, à cause de la nature différenciée des divers ordres du savoir et de leur rapport différencié à leur époque, exige un examen critique constant qui ne sera possible que grâce aux échanges interdisciplinaires.

II

6. Les considérations qui précèdent étaient nécessaires pour pouvoir aborder le coeur de notre sujet. Touchant la demande de pardon, Jean-Paul II parle d'"erreurs, d'infidélités, d'incohérences, de retards" (T.M.A. n. 33).

Il ne s'agit donc pas seulement de l'usage de moyens contraires à l'Evangile pour la défense de la vérité. Il s'agit, entre autres, d'erreurs. Comment l'entendre?

Les moralistes ne nous disent-ils pas que, dans certains cas, l'erreur – comme l'ignorance – supprime le caractère coupable d'un acte? Cependant s'il arrive ainsi que l'erreur excuse, il est des cas où l'erreur est coupable dans ses causes: négligence, précipitation, manque de l'information requise peuvent aboutir à une erreur. Dans le domaine pratique, comme dans le cas d'une erreur de diagnostic de la part d'un médecin entraînant de graves conséquences, l'erreur est punissable.

Il reste vrai que l'erreur et la faute sont choses distinctes et que nous n'avons pas le droit de les confondre.

Cependant le problème n'est pas totalement résolu pour autant. L'éthique, en effet, intervient au plan de la communication de la vérité. Rendre publiques des faits pénibles qui appartiennent à la vie privée de quelqu'un, c'est se rendre coupable de diffamation, acte punissable en certaines circonstances. Dire la vérité, comment la dire, cela pose une question de conscience au médecin, ou à l'éducateur quand il s'agit d'informer des mineurs. Devant un danger comme une épidémie, les autorités, afin d'éviter de semer la panique, n'ont pas à dire tout, ou doivent le dire progressivement. Enfin, on connaît les secrets militaires, qui ne sont pas sans poser des problèmes pour l'éthique de la recherche.

Ces quelques exemples illustrent une donnée importante: les détenteurs de certaines connaissances doivent tenir compte, dans la communication et la divulgation, du bien de la société ou de la protection de certains secteurs de la population. Certes le jugement sur l'opportunité ou la non-opportunité de cette divulgation est chose délicate; les abus sont toujours possibles, et c'est pourquoi il est souhaitable que la loi donne des directives et fixe des limites. En règle générale, et en dépit des cas particuliers que je viens d'évoquer, la meilleure défense de la vérité est la libre discussion des idées, ce qui requiert la compétence des interlocuteurs et une certaine maîtrise des dossiers.

On pourrait encore évoquer ici, en contraste avec l'exigence d'universalité qui est propre au savoir comme tel, les problèmes posés par la rivalité, je ne dis pas l'émulation qui est une bonne chose, qui oppose entre eux certains groupes de chercheurs, rivalité provoquée par la nécessité de trouver des fonds de financement. Il y a là tout un domaine de l'éthique de la recherche, que je me contente de signaler.

7. J'en viens à la question centrale. Pourquoi l'autorité religieuse intervient-elle dans le domaine de la vérité, étant entendu qu'il s'agit de la vérité religieuse? Disons d'abord qu'elle n'a pas compétence pour intervenir dans le domaine de la recherche scientifique comme telle. Si cependant elle intervient, c'est à un double titre. Ou bien, non pas une vérité scientifique en elle-même, mais sa théorisation philosophique, entre en contact avec la vérité religieuse. Ou bien il s'agit d'une recherche dont la finalité est pratique et qui est menée directement en vue d'interventions sur l'homme. Ce

qui est en jeu dans ce cas, c'est la spécificité de l'homme et l'intégralité de son humanité. La recherche ne peut ignorer la dimension éthique qui est présente dès qu'il est question de l'homme.

Ces précisions étant posées, nous devons nous interroger sur l'attitude de la raison humaine face à la Révélation. Nous parlons en d'autres termes de la nature de l'acte de foi.

Et si nous parlons de la structure de l'acte de foi, c'est parce que le Magistère est au service de la foi, qui est la foi de l'Eglise.

En effet, la foi, dans la conception chrétienne, comporte toujours une bipolarité: elle est engagement de la personne et elle est confession de l'appartenance à la communion ecclésiale.

Croire c'est donc accueillir une Parole qui nous vient de Dieu, et qui nous parle de Lui et de ses desseins de salut; la connaissance ainsi reçue n'est pas de soi accessible à la raison puisant dans ses seules ressources, elle dépasse les forces de la raison. C'est ce qu'indique le mot traditionnel de mystère, qui, en théologie, ne veut pas dire ce qui n'est pas encore connu mais le sera un jour, ni encore moins ignorance ou irrationnel. Si la réflexion théologique se nourrit de mystère c'est parce que celui-ci, tout en débordant les limites naturelles de la raison, est pour celle-ci source d'intelligibilité.

A cause donc de la nature de son objet, le croyant ne peut pas en avoir l'évidence. Il s'appuie, comme nous l'avons dit, sur le témoignage de témoins, dont il a reconnu la crédibilité. Cette non-évidence comporte deux conséquences. La première est la suivante: puisque, pour son adhésion, le croyant ne peut pas compter sur l'évidence que requiert notre raison pour un plein assentiment, quelle que soit la forme d'évidence, l'acte de foi comporte toujours une dimension volontaire, la volonté suppléant à la part de non-évidence qui ferait de l'adhésion un acte contenu dans les limites de la seule raison. La seconde conséquence est que l'acte de foi, si l'on fait abstraction de la grâce pour ne considérer que sa seule structure psychologique, est, par rapport à d'autres actes de la raison, imparfait. Saint Thomas fait ossserver que la foi, en vertu de sa non-évidence, comporte une sorte d'inquiétude, *irrequietudo*. On comprend aussi pourquoi la foi est comme habitée par un élan eschatologique, qui la fait aspirer à la claire vision.

8. Les aspects de la foi chrétienne que j'ai sommairement énoncés nous aident à comprendre la raison d'être et les finalités d'un Magistère de l'Eglise.

Le Magistère se situe dans le prolongement et au service de la Parole de Dieu. Celle-ci nous étant donnée d'en haut demande de la part du croyant un acte d'obéissance et de soumission. C'est pourquoi, au service de la Parole, le Magistère se prononce, quand il se prononce et selon qu'il se prononce, avec autorité.

La théologie s'est interrogée sur la nature, sur les modalités d'exercice, et sur les degrès de cette autorité. Selon la foi catholique, cette autorité, dans l'exercice de son service, jouit de l'assistence de l'Esprit Saint.

Cette assistance atteint son point extrême là où il s'agit de déclarer l'authentique contenu de la foi. Cette assistance alors jouit de l'infaillibilité, c'est-à-dire qu'elle est garantie de l'erreur. À mon avis, pour notre sujet, nous n'avons pas à nous arrêter à ce type d'assistance, dont le champ d'exercice est clairement délimité.

La grande majorité des interventions du Magistère ecclésiastique se situent en deçà. Son autorité est certes ici encore engagée et jouit d'une assistance de l'Esprit, mais qui ne va pas jusqu'à exclure la possibilité de l'erreur. Ici il arrive que le Magistère se trompe, ce qui ne veut pas dire qu'il se trompe toujours! Et dès lors que son autorité est en jeu, du fidèle est requise une attitude d'accueil, de docilité bienveillante, conforme à la nature de l'autorité qui se prononce.

Pour désigner ce type d'intervention, la théologie parle de pouvoir canonique et d'assistance prudentielle. Le pouvoir canonique s'exerce dans l'ordre des directives pratiques, mais il s'étend aussi à des questions doctrinales, comme nous l'avons vu dans le cas de Galilée. C'est à propos de lui que peut se poser la question du pardon et, préalablement, celles de correction et de réhabilitation.

À travers les directives de cet ordre, le Magistère exerce son ministère pastoral. Celui-ci vise l'ensemble des fidèles, ou des portions du peuple de Dieu particulièrement exposées. Son but est de préserver la foi et de mettre en garde contre des obstacles sur la voie du salut.

Soulignons que de telles directives, dans la mesure où elles entendent répondre à un défi surgi de circonstances particulières à un moment précis de l'histoire, comportent une part de contingence. L'autorité est-elle toujours suffisament informée, se montre-t-elle suffisament attentive aux signes des temps, tient-elle suffisament compte des leçons de l'expérience? ce sont là des questions qu'avec d'autres du même type, il est légitime de se poser. La méditation sur les faux-pas du passé doit aider qui exerce l'autorité, à le faire dans la conscience de sa fragilité, *cum timore et tremore*, en suppliant pour obtenir les lumières du Ciel.

Ainsi, dans l'histoire de l'Eglise, des directives ont pu créer des tensions déchirantes pour la conscience de croyants sincères. Disons que dès que les failles ou le caractère obsolète de semblables directives sont perçus, elles sont du même coup désavouées et se trouvent nulles et non avenues[1].

En écrivant ces lignes, je pense à un certain nombre de directives en matière d'interprétation de la Bible données au début du XX° siècle, alors que dominait l'exégèse libérale d'inspiration rationaliste. Ces directives étaient avant tout défensives. Elles ont posé de douloureux cas de conscience à des chercheurs catholiques comme le P. Lagrange. Elles visaient sans doute à protéger la foi du peuple chrétien, nullement préparé à subir le choc de cette exégèse et de son esprit. On est allé à l'immédiat, sans discerner toujours les vrais problèmes qui se posaient. Mais ignorer un problème, ce n'est pas le résoudre. Aujourd'hui, tout cela heureusement appartient au passé.

9. De ce qui précède, se dégage une conclusion. Une des tâches de la théologie est sans doute cette (re)lecture de l'histoire de l'Eglise et notamment des interventions du Magistère dont nous venons de parler.

Pour être authentique, la critique, car cette relecture est oeuvre de critique, doit obéir à un certain nombre de critères, et éviter un certain nombre d'écueils.

Le premier écueil est celui de l'historicisme. Il consiste à éliminer le problème en posant en principe que toute doctrine et toute affirmation sont entraînées par le flux du temps et portent en elles-mêmes la marque du provisoire et leur caducité. Il n'y aurait aucune vérité permanente.

Le second écueil est l'anachronisme. En effet, pour juger d'un événement du passé, ici d'une prise de position doctrinale de type prudentiel, il faut la situer dans son contexte historique et culturel. Certaines interventions étaient justifiées à leur époque, qui ne le seraient plus aujourd'hui. Elles ont perdu leur pertinence: ce n'est pas une raison suffisante pour dire que leurs auteurs se sont fourvoyés.

En réalité, il faut examiner cas par cas; ainsi l'exige la nature de l'histoire.

À ce propos, nous pouvons proposer certaines remarques.

---

[1] Cf. à ce sujet Cardinal Charles JOURNET, *Le caractère théandrique de l'Eglise source de tension permanente*, in *L'Eglise de Vatican II*, Paris, Le Cerf, 1966, Unam Sanctam 51 b, pp. 308-310. Le même auteur a longuement traité de ces questions dans son monumental ouvrage *L'Eglise du Verbe Incarné*, I *La hiérarchie apostolique*, Editions Saint-Augustin, 1998, notamment ch. VII, p. 676-776.

Il n'est pas rare que l'émergence d'idées nouvelles non seulement bouscule des habitudes mentales, mais encore, à cause des résistances rencontrées, prenne une forme polémique qui à son tour suscite une riposte elle aussi polémique. L'histoire des idées en Europe, y compris des idées religieuses, est porteuse de beaucoup de passions.

Une idée pour s'imposer a besoin du temps. Elle doit connaître des maturations, être soumise à l'épreuve des objections, on doit en mesurer les conséquences. En percevoir du premier coup les fondements et les prolongements demande une perspicacité qui n'est pas toujours donnée. T.M.A. n.33, cité plus haut, parle de retards.

Si j'ai fait référence à la dimension d'engagement de la foi, dimension qui lui est intrinsèque, c'est à cause des attitudes de docilité qui sont requises du croyant, sous la mouvance de la foi et en cohérence avec la foi. Mais aussi parce que ce peut être une tentation pour l'autorité de régler certains problèmes, en eux-mêmes intellectuels, par voie disciplinaire alors qu'il s'agit plutôt d'expliquer, de persuader et de convaincre.

D'une manière semblable, quand l'autorité est amenée à condamner un écrit, ce qu'elle fait en réalité c'est d'en déclarer l'incompatibilité avec le message de la foi et d'alerter la conscience des chrétiens sur cette incompatibilité. Mais il convient de souligner fortement qu'une telle condamnation porte sur des idées, non sur la personne. Se tromper, exposer des idées fausses doit être distingué d'un délit.

10. Tout cela nous paraît clair aujourd'hui, pour un double motif.

L'un tient à l'histoire et à des siècles révolus dont cependant la mémoire à perduré longtemps comme une sorte d'idéal perdu qu'il s'agissait de reconquérir. Je parle du régime de chrétienté et de sa nostalgie. Ce régime était caractérisé par le lien étroit entre l'Eglise et l'Etat, la société étant une société composée de chrétiens. L'identité religieuse avait ainsi une incidence politique et juridique directe, à tel point qu'une dissension au niveau religieux signifiait aussi une rupture par rapport au corps politique. Le recours au bras séculier s'explique par cette situation. De même, à l'inverse du pluralisme aujourd'hui reconnu, l'unanimité dans la croyance était retenue comme une condition du bon fonctionnement de la société politique. Il s'agit là d'une problématique qui est dorénavant révolue.

Une dernière question se pose. Pourquoi la demande de pardon et ce retour sur le passé? Je laisse ici de côté la signification théologique de la demande de pardon[2], pour ne retenir que deux points. D'abord, ce retour sur le passé n'a de sens que s'il permet d'aborder avec plus de lucidité le présent et l'avenir. Et si cela est possible, c'est que l'Eglise a une vision positive du sens du temps et de l'histoire dont elle entend lire les signes. Autrement dit, derrière cette démarche, il y a la conviction qu'au cours du temps la conscience évangélique, je veux dire des exigences de l'Evangile, progresse. Dans sa marche dans l'histoire l'Eglise apprend, réfléchit, mûrit.

L'examen de conscience requiert d'abord le travail des historiens, mais aussi une réflexion théologique sur l'histoire. Tel est le sens de la purification de la mémoire. Elle porte aussi sur les interventions qui touchent le domaine des idées considérées dans le contexte de leur émergence dans le temps. Il peut ainsi être question de corrections et de réhabilitations, de demandes de pardon pour les blessures infligées et les malentendus crées. Tout cela à la lumière d'une conscience sans cesse avisée et attentive aux exigences évangéliques.

---

[2] Cf. mon ouvrage, *Mémoire et Repentance*, Saint-Maur, éd. Parole et Silence, 1998, 114 p.

LOGIC AND UNCERTAINTIES IN SCIENCE AND RELIGION[*]

CHARLES H. TOWNES

Science and religion represent two different aspects of human understanding and different instincts which often seem *quite* different, yet can be closely related. Science, with its experiments and logic, tries to understand the order or structure of the universe. Religion, with its theological inspiration and reflection, tries to understand the purpose or meaning of the universe. These two are cross-related. Purpose implies structure, and structure ought somehow to be interpretable in terms of purpose.

At least this is the way I see it. I am a physicist. I also consider myself a Christian. As I try to understand the nature of our universe in these two modes of thinking, I see many commonalities and crossovers between science and religion. It seems logical that in the long run the two will even converge

Can we Really Separate Science and Religion?

For most of Western history science and religion were closely tied to one another. Theologians were intellectuals of their communities, and although science was more limited in scope it tended to be integrated with philosophy and theology. With the advent of experimental science during the Enlightenment, the practice of empirical research grew very rapidly and very successfully. Skirmishes between science and the Church signaled a change. Copernicus's heliocentric universe was condemned by the Roman Catholic Church in 1616 and Galileo was forbidden to defend it; Galileo's exoneration awaited Pope John Paul II just in recent times. By the nineteenth century open clashes between science and religion had become com-

---

[*] Reprinted from my article in the book *Science and Theology: The New Consonance,* edited by Dr. Ted Peters and published by Westview Press, Inc.

mon, notably with the battle between the theory of evolution and the seven day creation account in Genesis.

In our time it has become difficult for many to understand how one can put the scientific world view and the scientific method together with religion. Louis Pasteur, who was a very devout person, was asked the question: How can you be both a scientist and a person of faith? His answer went something like this: “Well, I do science in my laboratory. My home and my religion are separate.” That was all he could say.

What Pasteur represents is a sort of two-language approach: Whereas science provides the language of laboratory understanding, religion provides a private language of faith which is needed in our relation to other humans. Such an attempted separation is not uncommon today. I would put Pope John Paul II in the two-language camp. While he honors science and recognizes its importance, he seems to adhere to the view that these are separate tracks of thought which should not tell each other what to think. Science and theology should cooperate with each other in the common pursuit of the welfare of humanity; but, the Pope believes, in the final analysis they cannot teach each other very much.

On this the Pontiff seems to be in tune with our wider culture – what some call our two cultures – wherein we split apart the humanities and the sciences. Our cultural sensibilities separate religion and other humanistic affections from science like we separate warm from cold, the poem from the microscope, the living from the dead. We sometimes even separate nature from science, assuming that nature is warm and that this warmth can be apprehended only by the poet. The scientist, in contrast, allegedly invokes cold-hearted methods that are as deadening to nature as they are to the human spirit. Take William Wordsworth, for example:

> Sweet is the lore which nature brings;
> Our meddling intellect
> Misshapes the beauteous forms of things
> We murder to dissect[1]

Or, John Keats:

> Do not all charms fly
> At the mere touch of cold philosophy?[2]

---

[1] “The Tables Turned” in *William Wordsworth: Selected Poetry,* ed. Mark van Doren (New York: The Modern Library, 1950), p. 83.

[2] “Sonnet to Science,” in *John Keats: Poems,* ed. Gerald Bullett (London: J. M. Dent and Sons, 1974), p. 163.

Or, Edgar Allen Poe:

> Science, true daughter of Old Time thou art
> Who alterest all things with pondering eyes
> Why preyest thou thus upon the poet's heart
> Vulture, whose wings are dull realities.[3]

What these poets assume is a split between the aesthetic and the empirical, a rift between human affections and disciplined research. But a closer look will show that aesthetic affections are alive and well in the scientist. The vastness of the apparently limitless reaches of outer space combined with the intriguing complexities of the smallest microscopic things elicit an aesthetic response in the human soul. Nature communicates meaning; and science can actually facilitate this communication. Alexander Pope puts it this way:

> He who through vast immensity can pierce,
> See worlds on worlds compose one universe,
> Observe how system into system runs,
> What other planets circle other suns,
> What varied beings people every star,
> May tell why heav'n has made us as we are.[4]

Whether through the latest telescope, the microscope, or the landscape around us, we can see beauty in nature; and this beauty communicates meaning. Scientist Henri Poincaré testified to the aesthetic attractiveness of the twin facts of simplicity and immensity in nature. We seek out, he observed, the vast expanses of space and the microscopic particles of matter, in part because we take delight in them. Our aesthetic sensibilities are drawn to the vast and to the simple, the tiny and the remote.

Although science and religion are frequently separated and contrasted, I believe they can provide overlapping ways in which we apprehend the one universe of which we are a part. Nature gives voice to beauty, and beauty to meaning and purpose. The language of science may appear lifeless or deadening to some poets; but the scientist himself or herself is often sensitive to the beauty of nature, immensity of space, and the complexity of the material world.

Let us look at this again from a slightly different angle. The beauty of nature elicits a response from both our scientific and our poetic modes of understanding. Our aesthetic sensibility is triggered by our experience

---

[3] *The Complete Poems and Stories of Edgar Allen Poe,* texts established by Edward H. O'Neill (New York: Alfred A. Knopf, 1967), vol. 1, p. 28.

[4] Alexander Pope, "An Essay on Man," in *Alexander Pope's Opus Magnum, 1729-1744,* ed. Miriam Leranbaum (Oxford: Clarendon Press, 1977), p. 51.

with nature's beauty, and it comes to voice in both scientific and religious languages.

Note how beauty and truth seem to converge for both the poet John Keats and the physicist Werner Heisenberg. Keats said it this way: "Beauty is truth, and truth beauty."[5] Heisenberg argued that when nature leads us, by way of scientific analysis, to simple and beautiful mathematical forms, we are irresistibly impressed by the feeling that these forms must be "true"; that they must in fact reveal an actual feature of the natural world. We scientists, seeing a simple relationship that seems beautiful, intuitively think it likely to be true. Both scientists and theologians give themselves to the truth that transcends and invites us.

Similarities in Logic and Uncertainty

My own view is that science and religion are remarkably similar in spite of the great differences assigned them by our culture. They are remarkably similar, very simply because of who we are as people. It is people who author both science and religion. It is we who ask how to think about things and how to learn about things. We can expect similarities in approach to both science and religion because both emerge from the same human mind.

Science and religion not only share a common logic; they also share something else, namely, uncertainty. We must recognize that we do not know things for sure. Knowledge, even scientific knowledge, is less than absolute. As research proceeds we pick out a set of postulates which seem reasonable to us. We test those postulates with our experience or with experiments. We test to see what fits. Yet the postulates remain postulates. Some level of uncertainty regarding the validity of the postulates remains.

The mathematician Gödel proved that uncertainty is inherent even in the nature of our logic. Mathematics proceeds by employing a working set of assumptions and from these, using the rules of logic, proving something particular. Gödel proved that we can never be sure that the assumptions with which we started are even self-consistent, let alone true. The only way we may show that they are self-consistent is to appeal to a new set of assumptions, and from these try to prove the original set. But of course, this new set of assumptions is subject to the same uncertainty

---

[5] "Ode on a Grecian Urn," in *John Keats: Poems,* ed. Gerald Bullett (London: J. M. Dent and Sons, 1974), p. 192.

regarding self-consistency, and so on. Thus there will always be things which we assume to be true but which cannot be proved. Logic and uncertainty come together in a single package. And to take them seriously, there must be faith.

Reason Builds on Faith, Even in Science

Religion, with its theological reflection, builds on faith. Science too builds on faith. How? For successful science of the type we know, we must have faith that the universe is governed by reliable laws and, further, that these laws can be discovered by human inquiry. The logic of human inquiry is trustworthy only if nature is itself logical. Science operates with the faith that human logic can in the long run understand nature's laws and that they are dependable. This is the faith of reason.

Why would a scientist work day and night for a long period of time on a problem that is difficult to solve? For such motivation, he or she must have faith that the problem is solvable, and that there is an inherent logic in nature which his or her mind is capable of reading. Prior to solving a problem, the scientist works with faith in the as yet unseen reasonableness of nature.

Albert Einstein was such an example. For the final twenty years of his life he worked on a Unified Field Theory. As he worked, he reasoned that there had to be some form of a unified account of the laws of nature which warranted his effort to discover them, even though in the long run he did not achieve this goal. We scientists work on the basis of a fundamental assumption regarding reason in nature and reason in the human mind, an assumption that is held as a cardinal principle of faith. Yet this faith is so automatically and generally accepted that we hardly recognize it as an essential basis for science.

Revelatory Experiences

One might think that religion and its theology have a patent on revelatory experiences. One might also think that scientific discovery consists merely in reasoning based upon existing knowledge. But revelations of new knowledge can also happen in the process of scientific discovery.

One famous case of revelation was the discovery of the benzene ring structure. The German chemist Kékulé had puzzled for some time over how carbon could form benzene and similar molecules. The story is that one evening, partly dozing in front of his fireplace, he dreamt of a snake which curled around and took its tail in its mouth. He woke up. That's it – carbon atoms form a ring!

I have had such a revelatory experience. At the time I was working on what would become the maser and the laser, I had been researching ways of producing short waves for four or five years, but nothing I tried was producing the results I was looking for. And I was chairperson of a committee organized to consider what research was needed to produce short waves. Early in the morning just before a meeting of this committee in Washington, I walked out to a park to enjoy the fresh air. I sat on a bench looking at the azaleas freshly opened. And I asked myself: "Why can't we do this?" I went through the reasoning one more time, but this would not yield an answer. We ought to be able to use atoms or molecules, I thought. They are built in a way which produces short waves. But no, I'd been through that before. The problem was limits. posed by the second law of thermodynamics: you can't get more than a certain amount of power...Wait a minute! Wait a minute! The second law of thermodynamics doesn't have to apply if there is no definable temperature. I sat there for a few minutes. A revelation of sorts had occurred. I could see it in my mind. I took out a piece of paper and pencil and wrote down the numbers. Sure enough, the numbers made sense. One could build a practical short wave oscillator using molecules mostly in excited energy states and hence not describable by an ordinary temperature.

If we emphasize its setting, this story can even be endowed with a certain mystique. I had stayed overnight in a hotel with A. L. Schawlow. When I had awakened, he was still asleep. To avoid waking him I had slipped out. He was to become coinventor of the laser with me. The building looking out over the park was where Alexander Graham Bell had worked intensively but unsuccessfully on using light for communications, for which the laser has played one of its major roles. At the time, I did not even know about the closeness of Bell's former laboratory, but that was in fact the setting for this revelation.

Theologians might say that revelation both prompts faith and reflects on faith. As a research scientist, my faith came first and kept me inspired to work until a revelation occurred, one which confirmed my faith in the scientific endeavor.

Quantum Mechanics and Uncertainty

Despite our faith in the logic and reliability of nature, at the subatomic level we find counter-intuitive phenomena, generally understood by the discovery of quantum mechanics. Some of these phenomena must be thought of in terms of uncertainty, or to put it more strongly, of indeterminism.

Let us start with a question which has arisen frequently: Does light consist of particles or waves? Newton thought light was made of particles, but in the early part of the 19th century Thomas Young did interferometric experiments which convinced scientists that light is really made of waves. With the birth of quantum mechanics in the early part of this century, light took on aspects of both particles and waves. This duality is contrary to normal human intuition, and continues to be challenging. When we shine light on a glass window, some of it is reflected back while the rest passes through. Yet we should. and can ask: How does an individual particle of light, a photon, decide whether to bounce back or to pass through? Attempting to answer such a question leads to the Heisenberg uncertainty principle. According to this, we can never know for certain which particular photon will pass through the glass or be reflected. A fundamental uncertainty pervades the full extent of our knowledge of the physical world. The best we can do is predict the odds -the probability- that a given thing will happen, or that a given photon pass through or be reflected.

Causal determinism no longer applies. This is the conclusion derived from quantum mechanics, or from Heisenberg's uncertainty principle. Causal determinism seems to make sense at the level of day to day observation of any thing much larger than the atomic scale; but at the atomic level our science implies a heavy dose of chance operative in nature. Some scientists – for example Einstein – still convinced by their faith in the rationality of nature understood in terms of causal determinism, persisted in seeking to overcome uncertainty by positing the concept of hidden variables. This approach postulated hidden variables to represent as yet undiscovered forces which produce the quantum phenomena we observe. To these scientists the world of nature simply had to be deterministic, so such a force was assumed.

Bell's Theorem in the 1960s suggested a way in which the postulated existence of hidden variables could be tested. John Clauser at the University of California, Berkeley, first put the theory to experimental test, and revealed that no such hidden variables could be present. This has since been confirmed by many experiments. To his credit Clauser acknowledged that, even contrary to his own firm expectation, nature had spoken through an experiment announcing that no hidden variables exist.

With the advent of quantum mechanics, some religiously-oriented scientists such as Arthur Compton immediately claimed that God acts at the quantum level, and, together with nature, can make quantum events occur the way they do. But there is a basic problem with this approach. Granting Heisenberg's uncertainty principle, along with the rejection of hidden variables, science leaves no room for God to interfere. To insert God as a determining cause makes little sense when what is observed scientifically is that no causal determinant can be at work here.

Can we do Experiments in Religion?

Is it possible to perform experiments about religious questions? The key to success in scientific research is that an experiment performed by one scientist is in principle repeatable by another scientist and, if valid, will produce a confirming result. Experiments can be repeated. Is such a thing possible with religious subject matter? My answer is a mixed one.

On the one hand, experiments and experience go together. Experiments are organized experience, so to speak. We have to recognize, of course, that certain areas of human experience are not repeatable and therefore not subject to what is ordinarily called experimentation. Each day we see things and do things that affect the actions of other people; we read history and learn about the sequence of events that brought us to where we are today. Daily activities and historical understanding represent experience which is in many ways very much like experimental observations, but it is normally experience of unique and unrepeatable events. Religious experience typically belongs in this category, as does some of social science. Theology, which among other things reflects on human experience, relies heavily on the history of unrepeatable events. But we evaluate these, applying whatever logic we can muster, perhaps subconsciously, along with intuition, to form our religious views.

Some dimensions of religious life may well be confirmable. Doubting Thomas for example, following the Easter resurrection of the crucified Jesus, wanted proof. He wanted to touch the wounds of the corpse now living in order to overcome his doubt regarding the truth of the resurrection claim (John 20:26-29). It is not unusual for a person of faith to want the same confirmation of belief that a scientist wants to find in the results of an experiment. We might think of Thomas as the first empirical Christian.

Prayer may provide us with another example of religious experience subject to experimental investigation. A recent study by Dr. Herbert Benson at Harvard undertook experiments to determine if prayer for the sick or injured has any influence on their recovery. The results of this statistical study confirmed that, yes, prayer does in fact have a positive effect on the health of patients. The experiment was done with patients who knew they were being prayed for; an experiment without the patients knowing this still needs to be done.

Now, how should we think about such an experiment? Suppose we were to draw a strict line of separation between science and religion, what would we conclude? Prior to the experiment, prayer would have been considered strictly a religious phenomenon. Now that a successful experiment has been performed, it might then enter the domain of science. Yet prayer is prayer, regardless of the experiment. This is another reason why I do not agree with those who maintain a high wall of separation between science and religion. Instead, I would rather admit that science and religion are not discretely separated domains. Rather, they constitute two complementary modes of human understanding; and at least in some areas they share a common domain of knowing. In fact, I hesitate to put boundaries on either one, and expect that as we understand each more fully, they will more fully overlap.

Creation and the Anthropic Principle

One of the most significant points of shared interest between science and theological reflection is concern for the origin of the universe. What do we now know from science about the origin and history of the universe that may touch on what theologians believe about God's creating us and our world with a purpose? First, we now know that there was a unique time in the history of the universe. About 15 billion years ago it exploded with the "Big Bang" from a minuscular size to its present enormous extent. Afterwards, the sun and the earth came together, and life began. This is contrary to the intuitive beliefs of many scientists of the past that the universe has always been more or less the same; that there can be nothing unique about us nor in the history of our universe. What lies behind this beginning is the source of much scientific thought and speculation. The theologian can say that it was God's creation, and avoid the question of what then was God's origin. Scientists try to probe beyond this beginning, but we cannot avoid confronting the concept of a "beginning."

We have also learned from science that very special circumstances were necessary for us to be here. The early kinetic energy of the Big Bang explosion had to match the mass of material more closely than one part in a million million in order for the universe to both be long-lived as it is and also to develop galaxies and stars. The nuclear and electronic forces in atoms had to have just the right ratio for this universe to have the rich variety of chemicals needed for our life. The gravitational force and nuclear reaction properties had to be very well matched to allow formation of long-lived stars. Two energy levels characteristic of oxygen and carbon nuclei had to be remarkably well matched for both carbon and oxygen to be abundant, as we need them to be. These and other remarkable "coincidences" have led to articulations of the "anthropic principle " – that the natural laws must conform to what is needed for human life. But this is only a tautology since of course we are here. What is interesting is the apparently very special conditions required by human life.

Also of particular interest is the close tie between life and the nature of our planet earth. Many planets are likely circling other stars; and so life may not be rare. In principle we must suppose that life may have developed in many locations. Yet, when we took at all the planets within our solar system, our Earth looks unique. Jupiter, Saturn, and the other large planets are too cold, too gassy, and inhospitable for anything like our kind of life. Mercury is too close to the sun and hot. Mars and Venus seem at first glance to be similar to Earth. Although life may have existed in the past on Mars, today it is cold and without an appropriate atmosphere.

Earth's sister planet Venus, earlier thought to be a promising planet for life, we now know is covered with a heavy atmosphere of carbon dioxide and the surface is hot enough to melt lead. Actually, the atmospheres of both Venus and Earth are thought to have begun similarly, with carbon dioxide being emitted from their inner material and accumulating in the atmospheres of each. Yet, life started at just the right point in Earth's history, just before the greenhouse effect became overwhelming and the planet became too hot. Life on Earth started about a billion years after planet formation, at just the right point where it could change carbon dioxide into free oxygen. It continued to keep the carbon dioxide under control, preventing Earth from becoming overheated like Venus. Now how does one evaluate this? I hesitate to draw hard and fast conclusions. Yet these observations are impressive. Freeman Dyson faces the situation with the following statement:

> I conclude from the existence of these accidents of physics and astronomy that the universe is an unexpectedly hospitable place for our living creatures to make their home in. Being a scientist, trained in the habits of thought and language of the twentieth century rather than the eighteenth, I do not claim that the architec-

> ture of the universe proves the existence of God. I claim only that the architecture of the universe is consistent with the hypothesis that mind plays an essential role in its functioning.[6]

Regardless of what one may think this can say about God, what is striking here is that scientific evidence leads to a feeling and hypothesis that the course of natural history is guided at least in part by an intelligence and a purpose.[7]

Physicists have been brought much closer to questions of interest to theologians as they succeed in delving more fundamentally into the origins of our universe and the nature of physical laws. Relativity and quantum mechanics have also changed our basic concepts since the last century. Strict causal determinism, for example, has gone. And while as a result of developments such as relativity and quantum mechanics we now understand much more than we did in the nineteenth century, I believe physical scientists have become more modest about how completely we really understand our universe.

It is particularly striking that as our experiments and thoughts have penetrated new realms – high velocities and high gravitational fields in the case of relativity, tiny particles of atomic size in the case of quantum mechanics – our basic concepts have been altered, but without changing the validity of most of our previous physical laws under the circumstances where they were previously tested. For macroscopic objects we still teach, use, and intuitively think in terms of Newtonian mechanics, even though our views of its meaning have radically changed. For ordinary velocities and ordinary gravitational fields, we still use and think intuitively in terms of a simple three dimensional space and an independent time, even though general relativity provides a rather different basic view. This may lead to the conclusion that time-tested ideas, either in science or in religion, are likely to continue to have some kind of validity even if in the distant future we understand enough to revolutionize our thinking in either area.

---

[6] Freeman Dyson, *Disturbing the Universe* (New York: Harper and Row, 1979), p. 251.

[7] Elsewhere Freeman Dyson writes: "The universe as a whole is hospitable to the growth of mind. The argument here is merely an extension of the Anthropic principle up to a universal scale...the argument from design still has some merit as a philosophical principle. I propose that we allow the argument from design the same status as the Anthropic Principle, expelled from science but tolerated in metascience. The argument from design is a theological and not a scientific argument." *Infinite in All Directions* (New York: Harper, 1988), p. 297.

Chance in Biology

The biologists may at first seem fortunate because they have not run into brick walls such as physicists hit in finding quantum or relativistic phenomena that are so strange and different. But this may be because biologists have not yet penetrated far enough towards the really difficult problems where radical changes of viewpoints may be essential. In any case, biology is now in a stage where no basically new phenomena are obviously needed for its progress, and current work can be interpreted in terms of known laws of chemistry and statistics. We do not really know just how the first forms of organized life started nor whether initiation of life was very likely, even given favorable circumstances on Earth. We do not even know the details of under just what circumstances on Earth it began. Yet to many scientists, life seems a natural and almost automatic event given that the physical laws and nature of our planet turned out the way they did. Jacques Monod puts it strongly: "Chance alone is at the source of every innovation, of all creations in the biosphere."[8] Stephen Jay Gould says, "We are the accidental results of an unplanned process."[9] But some, like the evolutionist Ernest Mayer, are nevertheless impressed. He writes: "Virtually all biologists are religious in the deepest sense of this word...The unknown, and maybe the unknowable, instills in us a sense of humility and awe."[10]

I believe biology may yet encounter problems which may fundamentally change our views, and wish I could watch its development over the next century to learn whether this becomes true. For example, really understanding the human brain seems an awesome task. Clearly we can understand much more than we do at present. We can, for example, imagine "intelligent" computers designed to do many of the things our brains do. But can they have anything like the sense of consciousness or the sense of free will that humans possess? The brain is immensely complex. It contains ten billion neurons, each of which has about ten thousand synapses. This represents about a million gigabits of information, interacting in complex modes. The human brain can understand many complex devices. But we

---

[8] Jacques Monod, *Chance and Necessity* (New York: Random House, 1972), p. 112.

[9] Stephen Jay Gould, "Extemporaneous Comments on Evolutionary Hope and Realities," in *Darwin's Legacy,* Charles L. Hamrum, ed., Nobel Conference XVIII (San Francisco: Harper and Row, 1983), p. 102.

[10] Ernest Mayer, *The Growth of Biological Thought* (Cambridge: Harvard University Press, 1982), p. 81.

can wonder whether any device can ever really understand itself, or only other devices which are somewhat simpler than that which understands them. Can the brain really understand itself?

Free Will

What do we really know about free will? I suspect that every scientist, like most humans, assumes that free will exists. It is part of our everyday reality as human beings. With quantum mechanics the world is no longer deterministic. But present science says that the chance directions in which quantum mechanics allows it to develop cannot be influenced either by a divine force or by anything like the usual concept of free will. Yet although the usual concept of free will is not consistent. with our present understanding of science, we almost all assume we have some free will and live accordingly.

How can we understand our sense of free will as consistent with today's science? It is possible that free will as we experience it is a delusion. Perhaps it does not actually exist. Perhaps it can be explained simply as a delusion that has proven to have great survival value in the process of evolution. Religion, like free will, might also be explained as a delusion contributing to our evolutionary advantage, increasing the survival potential of human society. So perhaps we are just kidding ourselves when we think we observe ourselves making free choices or responding to God's will.

In spite of uncertainties, like so many others I have a fundamental sense that free will is there. It exists. I feel that I have free will and act according to it. I look around and make judgments about things. I make decisions. I take actions. I also have a sense of divine presence in the universe and in my own life and try to act out of the sense of freedom concomitant with this presence. Our sense of free will needs to be explained, or perhaps accepted rather than explained away. The same is true, I believe, of our sense of the divine. As we pursue scientific and religious understanding, how will our views of such matters develop?

Conclusion

Once the necessities of life are available, questions about its orientation, value, and meaning, which are the emphasis of religion, are more pressing and critical than those about the structure of our universe, the emphasis of science. This may be why human societies have developed and codified religious ideas much sooner than scientific ones. But in the last few centuries science has, by contrast with religion, made remarkable progress, and this has put emphasis on its methods and validity. Yet our understanding of both science and religion are dependent on human reasoning, on evidence, and on faith. And both involve profound uncertainties.

As humans, we face life. Decisions cannot be avoided; we need to choose our orientation, actions, and directions even if we understand imperfectly. Each of us decides in our own way. Yet we all make these decisions based on our experience, what our parents have told us, observations of the people and society around us, our understanding of human history, the evidence we have, and whatever logic and intuition we can muster. While assumptions and decision about our lives cannot be avoided, we also need to be open to change, listening for revelations and looking for new understandings of reality. Relativity and quantum mechanics have revolutionized science. We must be prepared for revolutions in our thinking, both in science and religion. But we can at the same time expect that our past reasoning and beliefs have important, even if imperfect, validity.

NATURAL THEOLOGY IN THE LIGHT OF MODERN COSMOLOGY AND BIOLOGY

RICHARD SWINBURNE

In this conference we are being told of many great discoveries of modern science about how the world works. I seek to persuade you that these discoveries in no way diminish, on the contrary they reinforce, the force of natural theology – of arguments from the existence and very general characteristics of the Universe, to the existence of its creator God. There are many such arguments which can be ordered by the generality of their premises – arguments from the existence of the Universe, from its being governed by laws of nature, these laws and the conditions of the Universe being such as to lead to the evolution of animals and humans, these latter being conscious, humans having certain limited powers to hurt or harm each other, etc. Having only limited time I shall discuss only the two arguments to the existence of God from there being laws of nature and their being such as to lead to the evolution of humans. The mistake made by the form of natural theology developed in the Aristotelian tradition in the Middle Ages was to suppose that such arguments are deductively valid. But fairly evidently they are not. If an argument from "there are laws of nature" to "there is a God" were deductively valid, then it would be self-contradictory to assert "there are laws of nature, but there is no God"; but that does not seem to be the case. "There are laws of nature, but there is no God" seems to describe a logically possible state of affairs.

I have argued, however, for many years[1] that these arguments have considerable probablistic force. Each one gives some probability to its conclu-

---

[1] See my *The Existence of God*, Clarendon Press, revised edition, 1991; and the short simplified version, *Is There a God?*, Oxford University Press, 1996. Much of this paper uses material published in these places and in shorter articles elsewhere.

sion; they are cumulative, and together they make the conclusion – “there is a God” – significantly more probable than not. I have sought to show how such arguments work with the aid of confirmation theory (that is, the calculus of probability, used as a calculus for stating relations of evidential support between propositions). I represent by $P(p|q)$ the probability of a proposition p on evidence q. I use Bayes’s Theorem,

$$P(h|e \,\&\, k) = \frac{P(e|h \,\&\, k)}{P(e|k)} P(h|k)$$

to elucidate the relation between the probability of a hypothesis h on evidence of observation e and background evidence k, and other probabilities. To use this calculus does not involve supposing that exact values can be very often given to the probabilities involved. Often, all we can say is that some probability has some rough value – more than this and less than that, and that in consequence some other probability has some other rough value – close to 1, or fairly high, or less than that. The calculus sets out in a formal way the factors which determine how observational evidence supports a hypothesis (or theory). The relevant points can be made easily enough in words, but less rigorously and with their implications less clear. The calculus brings out that a hypothesis h is rendered probable by observational evidence e and background evidence k, in so far as (1) $P(e|h \,\&\, k)$ (the posterior probability of e) is high, (2) $P(h|k)$ (the prior probability of h) is high, and (3) $P(e|k)$ (the prior probability of e) is low. Background evidence is evidence about how things behave in neighbouring fields of enquiry (e.g., if you are investigating the behaviour of argon at low temperatures, there may be background evidence about how neon behaves at low temperatures). But when we are dealing with big theories of physics, and above all theories of metaphysics, there are no neighbouring fields of enquiry, and so we can ignore k by putting k as a mere tautology. $P(h|k)$ and $P(e|k)$ will then have values determinable a priori.

We have two different ways of explaining events which we use and think it right to use all the time. One is the way of inanimate explanation, typical of physics and much ordinary-life explanation. Here an explanatory hypothesis consists of initial conditions and purported laws. We explain the expansion of some object by it being copper and being heated (initial conditions) and there being a law that all copper expands when heated. The other way of explaining events is the way of personal explanation, typical of psychology, history and much other ordinary-life explanation. Here an explanatory hypothesis consists of a person (or other rational being), their powers, beliefs and purposes. We explain the movement of my hand by me (person) having the purpose of catching your attention, the belief that I will do so by moving my hand, and my power at will to move my hand.

The first condition above ($P(e|h \& k)$ high) is satisfied to the extent to which you would expect to find e if h is true. Obviously a scientific or historical theory is rendered probable, in so far as the evidence is such as you would expect to find if the theory is true.

However, for any e you can devise an infinite number of different incompatible theories h_n which are such that for each $P(e|h_n \& k)$ is high, but which make totally different predictions from each other for the future (i.e predictions additional to e). Let e be all the observations made so far relevant to your favourite theory of mechanics – let's say General Relativity (GTR). Then you can complicate GTR in innumerable ways such that the resulting new theories all predict e but make wildly different predictions about what will happen tomorrow. The grounds for believing that GTR is the true theory is that GTR is the simplest theory. When k is a mere tautology, $P(h|k)$ is the intrinsic probability that h is true, that is, the measure of the strength of the a priori factors relevant to the probability of h. These factors are its scope and it simplicity. A hypothesis has large scope in so far as it makes many precise claims; and the larger the scope, other things being equal, the lower its intrinsic probability. But we can ignore this factor if we are comparing theories of similar scope, and, even when we are considering theories of differing scope, scientific examples show that simplicity is more important than scope for determining prior probability – for theories (which satisfy the other criteria well) of large scope are regarded as probable, so long as they are simple. The simplicity of a theory, like its scope, is something internal to that theory, not a matter of the relation of the theory to external evidence.

Let me illustrate the importance of the criteria of simplicity from an example when we are considering rival personal explanations. A detective investigating a burglary finds various clues – John's fingerprints on a burgled safe, John having a lot of money hidden in his house, witneses reporting seeing John near the scene of the burglary at the time when it was committed (which we summarize by e). He then puts forward a hypothesis (h) that John robbed the safe, which is such that it leads us to expect the clues which were found – $(Pe|h \& k)$ is quite high. But there are an infinite number of other hypotheses which have this property. We could, to take but one example, suggest that Brown planted John's fingerprints on the safe, Smith dressed up to look like John at the scene of the crime, and without any collusion with the others Robinson stole the money and hid it in John's house. This new hypothesis would lead us to expect the phenomena which were found just as well as does the hypothesis that John robbed the safe. But the latter hypothesis is rendered probable by the evidence, whereas the former is not. And this is because the hypothesis that John robbed the safe postulates *one* object – John – doing *one* deed – robbing the safe – which leads us to expect the several phenomena which we find. The simplicity of a theory is a matter of it postulating few entities, few kinds of entity, few properties, few kinds of property, and ways of behaving which are unchanging in simple respects. The latter, if we are postulating persons as our entities, involves attributing to them purposes, beliefs, and powers which are constant over time, or only change in regular ways. If we are postulating natural laws, it involves using few mathematical terms and mathematically simple operations.[2] Of course, many accepted scientific theories these days seem to some of us quite complicated, but they are accepted because they are simpler than any other theory which satisfies the other criteria equally well.

$P(e|k)$, the prior probability of e (which for tautological k, is an intrinsic probability) is a measure of how likely e is to occur if we do not assume any particular theory to be true. The normal effect of this term in assessing the probability of any particular theory h, is that e does not render h very probable if you would expect to find e anyway (e.g. if it was also predicted by the main rivals to h which had significant prior probability). $P(e|k) = P(e|h \,\&\, k)\, P(h|k) + P(e|h_1 \& k)\, P(h_1|k) + P(e|h_2 \,\&\, k)\, P(h_2|k)$ and so on for all the h_n rival to h (where all these together with h are such that at least and at most one of them must be the true theory in the field). This value will clearly be determined largely by the terms n for which h_n has a relatively high prior probability, and which give to e a relatively high posterior probability. To the extent to which rivals to h which give e a relatively high posterior probability, themselves have a low prior probability (in comparison with h), the posterior probability of h will be high.

The hypothesis that there is a God is the hypothesis of the existence of the simplest kind of being whch there could be. A physical being will have spatial extension and thus consist of parts. Persons, as mental subjects, *need* not have spatial extension. God is the simplest kind of person they could be. A person is a being with *power* to bring about effects, *knowledge*

---

[2] For a full account of the nature of simplicity, see my *Epistemic Justification*, Clarendon Press, 2001, chapter 4.

of how to do so, and *freedom* to make choices of which effects to bring about. God is by definition an omnipotent (that is, infinitely powerful), omniscient (that is, all knowing), and perfectly free person; he is a person of infinite power, knowledge and freedom; a person to whose power, knowledge and freedom there are no limits except those of logic.[3] In virtue of his omnipotence he will not be tied down to operating on the world and learning about it by means of a body, and so he will not have spatial extension. The hypothesis that there exists a being with infinite degrees of the qualities essential to a being of that kind is the postulation of a very simple being. The hypothesis that there is one such God is a much simpler hypothesis than the hypothesis that there is a God who has such and such limited power, or the hypothesis that there are several gods with limited powers. It is simpler in just the same way that the hypothesis that some particle has zero mass or infinite velocity is simpler than the hypothesis that is has 0.32147 of some unit of mass or a velocity of 221,000 km/sec. A finite limitation cries out for an explanation of why there is just that particular limit, in a way that limitlessness does not. Although the existence of anything at all is perhaps enormously improbable a priori, the existence of God (h) as the existence of the simplest kind of being there could be has a far higher intrinsic probability ($P(h|k)$) than does the existence of anything else (except in so far as the latter is rendered probable by the former). Taking the inductive procedures of science and history seriously forces that conclusion on us.

It follows from God's omniscience and perfect freedom that he will be perfectly good. For being omniscient, he will know which actions are good. The goodness of an action provides a reason for doing it; and being perfectly free, he will be subject to no irrational influences. The worth of an

---

[3] In the Christian tradition God is "three persons in one substance", i.e. three persons each of whom have the listed divine characteristics, and have an essential unity – the Son and the Spirit being eternally and necessarily caused to exist by the Father. Arguments to the existence of God are then best construed as arguments to the existence of God the Father, from which the existence of Son and Spirit follows – in my view by logical entailment. The simplicity of God which I consider in the text is the simplicity of God the Father – that a simple theory has complicated consequences does not make it any less simple. I ignore this complication in subsequent discussion, for the sake of ease of exposition. For my own developed account of the divine nature see *The Coherence of Theism*, Clarendon Press, revised edition, 1993; and *The Christian God*, Clarendon Press, 1994. See chapter 8 of the latter book, for why the existence of the Father entails that of the Son and Spirit.

action alone will move him to perform it. So if there is a God, he will seek to bring about good things; and being omnipotent, he will be able to do so. So it is not improbable that he should create a universe, an orderly universe, and within it embodied rational creatures such as humans. It is good that there should be a beautiful universe. Beauty arises from order of some kind – the orderly interactions and movements of objects in accord with natural laws is beautiful indeeed. It is a further good thing that there should be human beings who can choose between good and bad, make differences to themselves, each other, and the world; choose whether to grow in power and knowledge, and so choose whether or not to enter into a loving relationship with God himself. Limited power means power over a limited region of the world, that is a body; and growing in power involves using our bodies to control things at a distance. But we have to know which bodily movements will make what difference to the world, in order to have an effective choice of which differences to make to the world – and that involves there being regularities in the world which are simple enough for us to detect. We can then use them to mould the Universe for good or ill – to develop an agriculture, and to make houses and bridges or bombs and prisons, and to send humans to the moon. With e as the operation of laws of nature, and their being such as (with initial conditions) to lead to the evolution of humans, $P(e|h \& k)$ is not too low. But unless there is a God, it is immensely unlikely that any Universe would be governed by simple natural laws. For natural laws are not entities. To say that all objects obey Newton's laws is just to say that each object in the Universe behaves in a way that Newton's laws state, i.e. has exactly the same properties of movement in reaction to the presence of other objects, as does every other object. It is immensely unlikely that every other object should behave in exactly the same way – a priori, unless there was a common cause of their having the properties they do. And any other possible cause (e.g. many gods) is much less simple than God. (Even if you suppose some impersonal cause to be just as simple a postulate as God, the simplest kind of person there could be, there is no reason why it should bring about this sort of universe.) And, in a world with natural laws, it is immensely unlikely that there would be humans unless either God made them by a special creation, or made just those natural laws and provided just those initial conditions which would allow the evolution of humans from some initial state of the Universe.

In 1859 Darwin produced his explanation of why there were complexly organised humans and animals in terms of the laws of evolution operating on much simpler organisms. His explanation is surely correct. But the question then arises as to why there are laws of evolution which have the consequence that over many millennia simple organisms gradully give rise to complex organisms. No doubt becauuse these laws follow from the basic laws of physics. But then why do the basic laws of physics have such a form as to give rise to laws of evolution? And why were there the primitive organisms in the first place? A plausible story can be told of how the primeval 'soup' of matter-energy at the time of the 'Big Bang' gave rise over many millennia, in accordance with physical laws, to those primitive organisms. But then why was there matter suitable for such evolutionary development in the first place? With respect to the laws and with respect to the primeval matter, we have the choice, of saying that these things cannot be further explained, or or postulating a further explanation. In recent years scientists have drawn our attention to the strength of this argument by showing how 'fine-tuned' is the Universe. It needed a certain density and a certain velocity of recession of its matter-energy at the time of the Big Bang if life was to evolve; and increase or decrease in respect of density or velocity (or some other respects) by one part in a million would have made the Universe non-life-evolving. Likewise the physical constants of the natural laws had to lie within narrow limits if life was to evolve. If God made the natural laws and the initial state of the Universe, then – for reasons already given as to why he might well bring about humans – it is to be expected that he would give the initial state and the laws these features (or make some underlying laws – e.g. those of string theory – such that they gave the initial state + laws these features.) But if God was not responsible, the probability of such an initial state and laws of the requisite kind would be immensely low – even if there are laws of nature of some kind. With e again as the conjunction of the premises of our two arguments, $P(e|k)$ is not going to be too much greater than the top line of the right side of Bayes's Theorem – $P(e|h \& k)\ P(h|k)$ – because hypotheses rival to theism either have a far lower intrinsic probability than theism (e.g. the hypothesis that the Universe was created by a million gods)[4] or do not make it in the very least probable that e would occur (e.g. the hypothesis that chance determined the character of natural laws).

---

[4] Among the hypotheses rival to theism which make it probable that e would occur is the hypothesis that there are an infinite number of worlds, each with different kinds of law or different kinds of chaos and different kinds of initial conditions. But that seems a wildly less simple hypothesis than theism – to postulate an infinite number of (causally independent) entities in order to explain the occurrence of one entity runs against all the rules of inductive inference.

So arguments from the two phenomena which I have considered give significant probability to the existence of God. There is not time to develop the case further here, but my own view (argued elsewhere) is that when we add arguments from other phenomena and even when we bring into the equation arguments against the existence of God (e.g. from evil), we get a strong case for the existence of God.

THE PROGRESS OF SCIENCE AND THE MESSIANIC IDEAL

JEAN-MICHEL MALDAMÉ

My contribution to the Academy's discussion will begin with a passage from the Bible. Why this particular text? Because it is a 'file' corner stone of our culture. In fact, it justifies scientific research and the resulting development of technology. God addresses his people thus:

> 'And I will rejoice in Jerusalem, and joy in my people: and the voice of weeping shall be no more heard in her, nor the voice of crying. There shall be no more thence an infant of days, nor an old man that hath not filled his days: for the child shall die an hundred years old; [...] And they shall build houses, and inhabit them; and they shall plant vineyards, and eat the fruit of them; they shall not build, and another inhabit; they shall not plant, and another eat: for as the days of a tree are the days of my people, and mine elect shall long enjoy the work of their hands. They shall not labour in vain, nor bring forth trouble; for they are the seed of the blessed of the Lord, and their offspring with them. [...] The wolf and the lamb shall feed together, and the lion shall eat straw like the bullock: and dust shall be serpent's meat. They shall not hurt nor destroy in all my holy mountain, saith the Lord' (Isaiah, 65, 19-25).

This text repeats previous texts which are explicitly connected to the role of the Messiah (Isaiah, 11, 7; 62, 8; Za, 8, 4). It is important to evaluate the role played by the Messiah in various expressions of culture and in what founds modern thought. I would like to recall the exacting demands it involves within the scope of this session on 'Science and the Future of Mankind'. As a matter of fact, many elements quoted by the Prophet Isaiah have come true (to the benefit of developed countries) thanks to the progress of science – of fundamental science and of medicine. Science always has been, and remains more than ever before, instrumental in the conquest and mastery of the world. It has helped to make some of the Messianic experience voiced by Isaiah come true. It is therefore important to throw light upon the exact role of biblical Messianism, which bears within it the sign of happiness.

I. MESSIANISM

The concept of the 'Messiah' can be traced back to a tradition based on the promise made to David when he founded the City of Jerusalem. The Prophet Nathan said to him – speaking in the name of God – that God's blessing would rest on his house, and that a king would arise from his offspring who would establish perfect justice and bring prosperity to his people (2 Sam 7, 1-17).

The word 'Messiah' has ever since served to designate a man consecrated by God, who would bring happiness and prosperity to all people along the lines of the picture drawn by the Prophet Isaiah. Through the presence of God (marked by this anointing) he would be at the origin of their happiness and would bring about justice and prosperity.

This hope was put to the test with a twofold effect: first, it resulted in an idealisation of Israel, and secondly in a widening of the Messianic expectation to the dimensions of the world.

1. *The Promised Land*

In the founding biblical texts, presented to us as a sort of memory coming from patriarchal times, the territory of Israel is idealized. It has become 'the promised land', 'a land flowing with milk and honey' (Ex 3, 8; Nb 13, 27). These phrases symbolize the abundance of cattle and the fertility of the soil in a world of cultivated lands, but also the wild lands where bees gather nectar. The ultimate symbol of this land is a cluster of grapes which was so large that it took two men to carry it on a stick – according to the emblematic text which sought to express God's benediction:

> 'And they came unto the brook of Eschol, and cut down from thence a branch with one cluster of grapes, and they hare it between two upon a staff; and they brought of the pomegranates and of the figs' (Nb. 13,23).

2. *The Land Looked Forward to by the Exiles*

The expression 'Promised Land' took on a more radical meaning at the time of the Exile.

Firstly, the exiles idealised the land of their childhood and passed on enchanted memories to their children. They forgot the difficulties, the toil and the labour, the aridity of the soil, the scarcity of water and the precariousness of peace with their neighbours, and imagined a period without faults. This is a repeated process with exiles, the world over.

Secondly, a new dimension of memory appeared, as a source of hope: the exiles gave a spiritual value to their country. Thus the Promised Land was depicted as having even richer attributes through a process which involved drawing on the universal resources of primary symbols. The desire for that Land took form and substance within the framework of a tale structured as a myth, i.e. of a rational explanation, operating within the language of images. In this idealising process, the exiled transformed the Promised Land into Paradise.

The word ‘Paradise’ deserves a word of comment: it is of Persian origin and means ‘garden’: an image of bliss in arid countries. Coined at a time of exile, under Persian influence, the word ‘Paradise’ occurs in a tale which is about what the people have lived through: first, the gift of the earth, represented as a garden of happiness; then the transgression; then the exile; and finally the expected salvation. But the biblical text which universalizes the experience of Israel in exile is not just a nostalgic evocation of the Past: it also looks forward into the Future, for a Holy Land given by God.

3. *Happiness without End*

The Exile came to an end when the Persians allowed the restoration of Israel. But this was a disappointing experience. The craving for happiness was also frustrated. Only those who have come back, at the end of a long journey, to the places where they had a happy childhood can understand this psychological process. There were many who suffered from disenchantment amongst those who dwelt in the Promised Land, after it was restored to them. Only a prophetic minority did not remain frustrated. The return to the Land of the Fathers was for them an opportunity to give hope a fresh start, under the guidance of the Prophets whose precepts were conveyed by the Bible. In this work of faith, a more universal dimension appeared.

The word ‘exile’ came to mean no longer the separation from the ancestral land, but the human condition, considered as the consequence of a Fall. The tale enlarged to the point of embracing all of mankind, represented by the patriarch Adam, who stands for mankind in its entirety. Thus the scribes who wrote the Bible gave a universal dimension to transgression and the Messianic hope: Adam's mysterious son, referred to in Genesis 3, 15, will crush the head of the snake which represents evil, according to what – literally – God said to the snake: 'and I will put enmity between thee and the woman, and between thy seed and her seed; it shall bruise thy head, and thou shalt bruise his heel.' The word 'seed' refers to a Messiah whose coming is expected from within the lineage of David and Solomon.

Moreover, the end of exile does not mean returning to a land which was formerly inhabited, but reaching a reality which is more beautiful than what explorers can say about visited lands, more beautiful even than what has been experienced during a happy childhood. Paradise regained is not only a land flowing with milk and honey, but a place where the wolf shall lie down with the lamb, where the calf and the bear shall feed together, and where the child shall play around the hole of the asp, according to the Prophet Isaiah (Is 11,1-9). The whole of creation will be restored to its primal purity.

The place of happiness is not only agrarian or arcadian; it also has an urban expression. It is no longer a Jerusalem which can be frustrating for those in distress, it is the New Jerusalem whose walls are made of precious stones, and whose streets are paved with light, according to the Prophet Isaiah's words, which were repeated by John in his Apocalypse (Is 54, 11-12; Ap 21, 11-21). The vision of future life is that of a happiness which breaks away from present limits imposed by time and space.

Conclusion

These texts are the foundation of hope, a hope which does not refer to a world which us purely spiritual but to a transfigured material world. Within the framework of my reflection on the origins of modern science, I feel confident that this vision of the future and this hope for happiness are together one of the main sources of modern culture, a culture in which scientific research and its application have allowed the Prophets' dreams – as illustrated by the long quotation from the Prophet Isaiah – to come partly true. It is now important to understand how this has come about.

II. THE FOUNDING PROJECT OF MODERNITY

In western civilisation the desire for happiness took on a particular form at the beginning of the sixteenth century with the great discoveries of that epeoch. The discovery of America compelled man to reconsider the map of the world. It was made clear that Paradise, which the ancients had placed in the East behind the high mountains and the burning sands of the desert, and which was thus inaccessible, was not a place but a symbol. It thus became impossible to read the biblical texts from a historical point of view as St Augustine and the medieval scholars had done. In order to locate the place of happiness a new word was coined: the word 'utopia',[1] which expressed the idea of hope in a happy world.

1. *The Birth of Utopias*

1. The word 'utopia' was coined by Thomas More.[2] In his work, published in Holland in 1516 and in London in 1518, which presented itself as fiction, he depicted an ideally happy life, not a purely spiritual eternal life but its present-day prior-experience. One of the major features of this ideal city was the fact that reason played a major role: the reason in question being that as conceived by the humanists, a conquering reason.

For Thomas More, men – after being purified by ordeals, despotism and religious wars – are allowed to find a refuge on an island of perfect happiness. The wish to reform the Church has led to the horrors of war and dictatorship conducted in the name of faith: Savonarola in Florence and Calvin in Geneva. As a reaction to this misuse of religion to promote violence, Thomas More – with a humour made up of subtlety, a touch of scepticism, and occasionally stinging irony – offers the enchanting picture of an island where everyone is happy thanks to the right use of Reason.

Reason rules over the activities of everyone. On the island of Utopia no one is allowed to be idle. Every person works, happy to earn his or her

---

[1] The word 'utopia' was coined by the humanists in the sixteenth century in order to project their desire for a happy life into the future. It is nowhere to be found, which means that it cannot be identified with past realisations or mistaken for a contemporary model. It is not exactly the Platonic myth of Atlantis, a vanished city, nor that of Priest John's kingdom looked for by Marco Polo, nor the happy Arabia dreamt of by the Romantics, nor even the islands of the Pacific, which the explorers and conquerors of the vast universe considered paradise. Utopia is the formulation of a reformer's political project. See on this theme Raymond Ruyer, *L'Utopie et les utopies* (Paris, PUF, 1950), and Jean Servier, *L'Utopie* (Paris, PUF, 1979) and *Histoire de l'Utopie* (Paris, Gallimard, 1991).

[2] Thomas More (1478-1535) was an English statesman, an ambassador of England and the Chancellor of the Exchequer. He was Henry VIII's counsellor and prime minister, but eventually dissociated himself from him to remain faithful to the Church of Rome. He died on the scaffold, proclaiming himself 'the king's good servant, but God's first'.

living. Work is varied, and each person in turn goes from one job to another. Free time is devoted to music and the fine arts. Religion is free. Gold is considered a vile, worthless metal. Moreover, in order to avoid the misuse of power, there are no secrets about people's private lives. The island of Utopia is thus a perfect city and offers all the advantages of idealised Jerusalem and Athens.

2. The work of Thomas More was written in connection with that of his friend Erasmus – the master of humanist studies.[3] In his *Praise of Folly* (1509), Erasmus's statements about his projects of reform are carried forward along a pathway of derision and the spectacle of a world turned upside down. In accordance with St. Paul's phrase, literally construed, 'because the foolishness of God is wiser than men' (1 Cor 1,25), Erasmus proposes to reform society and the Church in order to bring about a reign of peace.

3. We find a different vision of humanism in Rabelais.[4] A Franciscan monk, he was a worthy disciple of More and Erasmus. The abbey of Theleme represents the union of an ascetic ideal and a craving for joy through an education based on genuine science, as opposed to the futile scholastic quarrels. The main subject taught in this abbey is joy, ant this abbey which is thus different from monasteries, which are associated with fruitless penance! The abbey of Theleme is like an ark built to convey – beyond the waters of a new Flood – an ideal of serene science, righteous living, courteous manners, and free thinking.

4. A similar approach is found in the work of the Italian Tommaso Campanella.[5] The son of a workman, he was a monk intent on reforming

---

[3] Erasmus was born in 1469 and died in 1536. He is the figurehead of European thought: he lived not only in his native country, the Netherlands, but also in England, in Italy, and in Switzerland: Louvain, Oxford, Rome, Basel. He was a counsellor to Charles V and Pope Julius XI, who wanted to make him a cardinal – an appointment he refused. He was the apostle of peace, advocating the union of Christian European States. His studies are the foundation of classical humanities.

[4] François Rabelais was born in 1494 and died in 1553. He was not a classical philosopher, but his work is full of humanist erudition and can only be understood with reference to the philosophical tradition (Socrates, Plato, Pythagorus, Democritus) and to his criticism of medieval doctors.

[5] He was born in Southern Italy, in Stilo (1568) and died in Paris in 1639. He was a Dominican. He played an important political role, taking an active part in the rebellion of the southern Italian regions against the despotism of the empire. He was imprisoned with those who had been defeated in Naples. On being made free again, Pope Urban VIII made him his private counsellor. He spoke in defence of Galileo in 1633. But he sided with France and had to go into exile.

the Church who was sent to prison because of his insubordinate character. While in prison, in Naples, he wrote *The City of the Sun* in 1602. The book, published in 1623, is about an ideal kingdom where men are ruled by a priest-king-philosopher, with the assistance of three dignitaries: Power, Wisdom and Love. Power is responsible for peace and order; Wisdom looks after science and the arts; and Love takes care of the relationships between men and women, and also between the generations, so as to ensure a harmonious transmission of knowledge. In the City of the Sun all people worship God as the Father. A strong bond of brotherhood makes people live in peace with each other. Science plays an all-important role because it allows man to read the Great Book of Nature.

5. As a last form of utopia, one could mention that promoted by Francis Bacon[6] at the end of the Renaissance. He expounded it in the *Novum Organon,* which in Anglo-Saxon culture is the equivalent of Descartes' *Discourse on Method.* This work by Bacon presents a post-Copernican vision of the world: the world is no longer centred around the earth but around the Sun, which, according to Kepler, is more worthy of God's creation.

As far as our intersts are concerned, Bacon's most important work was *The New Atlantide* (1627). It deals with life on an island where morals are pure, where family virtues are honored, and where prostitution is unknown (even among sailors!) Right in the middle of the island stands Solomon's House, where wise men know how to grow wonderful plants which yield plenty of fine-tasting fruit. Men can move through the air and under the water. The country is governed not by tradesmen but by researchers, who are also called 'merchants of light'. They gather universal knowledge and build machines which enable artisans to practice their craft in a good way and without effort. Men move around without any difficulty; they communicate from a distance; they can fly through the air; and reach the bottom of the sea. Science not only provides a complete mastery of the technical, it also enables man to penetrate the secrets of the universe.

This brief glance at the main utopias shows how the dream of happiness gathered new strength with the great discoveries of the world and the scientific revolutions.

These texts were written by political and religious men who played an important part in society and had major responsibilities towards princes,

---

[6] 1561-1626. He had a legal and scientific background. He was close to Queen Elisabeth and was appointed Chancellor of the Exchequer under King James I. His principal interest was science.

kings and popes. The texts show how a new ideal was forged in relation to the use of Reason. Reason is something which keeps passions at bay and gives access to universal values. They also show that happiness is not an abstraction but something which is concrete, something to be enjoyed in a transfigured present time.

2. *The Realisation of the Ideal*

These texts talk to us because they have been fulfilled in diverse ways. I shall not discuss each one in detail but provide general configurations and contours of relevance to our subject.

2.1 *The conquest of the world*

The first realisation was the conquest of the world. The founding of the United States of America was achieved by men and women who wished to fulfill their goals in a land which they thought was virgin. Emigrants went there to survive famine but also to escape the persecution and the narrow-mindedness of the 'old world'. They founded States based on a utopian belief in liberty, human rights and happiness.

Colonisation was nourished by such a vision. In schools of administration, people learnt that they were supporting civilisation and leaving behind the quarrels of the past.

Urbanisation accompanied the movement: architects built cities according to geometrical rules. The twistings and turnings of streets gave way to constructions based on the circle, the square and other regular features. Such a project was founded on what utopians had said. The freshly revived myth of the golden number also illustrated this desire to make the terrestrial city a replica of the ideal celestial city. Reason organized space in perfect harmony with the cosmos, and since – according to Galileo – the world was written in a mathematical language, appeals were made to the ruler and compass and references were made to the science of the architect and engineer.

The mastery of time, made possible by the clock and the chronometer, also illustrates this desire: happiness lay in a well-shared, fairly measured, time which made justice and a just recompense possible.[7]

---

[7] See Lewis Mumford, *Technique and Civilization*, (Paris, 1950); David Landes, *L'heure qu'il est: la mesure du temps et la formation du monde moderne* ['*What time it is: the measurement of time and the formation of the modern world*"] (Paris, Gallimard, 1987).

Human fertility was also mastered and the renewal of generations was taken care of, and this with a special concern for what was called eugenics, i.e. the wish to eliminate genetic illnesses and ensure that the future was totally dedicated to health.

2.2 *The development of science and technology*

Science was the major development. Descartes said that man should become 'the master and the owner of nature'. This is something which man has gradually accomplished.

Let us consider the great scientific and historic explorations which were carried out in order to achieve greater and more effective knowledge of the world: the classification of human beings implemented by Linnaeus as early as the seventeenth century, then the orderly distribution of all living species on the great tree of evolution; the study of languages and of the structure of language; the understanding of the deepest parts of matter; the mastery of energy, particularly of electricity, which was rightly termed 'fairy electricity'; and the mastery of life and of the knowledge of its origins.

In brief, the wished-for project came true, along the lines of what was called, as early as the eighteenth century, *progress*. The progress of reason did not originate only in the sciences: it was also applied to the political world, which was eager to place itself under the rule of reason. An illustration of this can be found in Jules Verne's works. It is worthwhile reading them during adolescence, at an age when one dreams of submarines, air travel, voyages to the moon, canons serving peace, and the infinite extension of man's power over nature.

Enlightened despotism, and the middle-class republican ideal, as well as (paradoxically) the expressions of socialism of the nineteenth century, fed on that hope. Utopia acquired many different faces during the nineteenth century including the various kinds of socialism described for that very reason as 'utopian'. They proposed a society where everything is shared and where greed is abolished by giving to each according to his needs and expecting from that person that he gives according to his means. Such approaches are numberless. They can be traced back through the forms of European socialism marked by the Christian tradition. We encounter the same thing in Charles Péguy's early writings, in the form of the phenomenon of 'the harmonious city'.[8]

---

[8] Charles Péguy, *Marcel. Premier dialogue de la cité harmonieuse*, (1898), in *Oeuvres en Prose*, I (Paris, Gallimard, 1965), pp. 12-86.

Those utopias mobilised all the efforts made in favour of science. But their successes were achieved at a very heavy cost – hence the time of disenchantment which later followed.

3. *The Time of Disenchantment*

During the twentieth century (which has just come to a close) we lived through a time of disenchantment. The desire for progress gave birth to disappointment, which is, so are we told, at the heart of what should be called 'post-modernism'.

3.1 *The effect of the great war*

What died, on the battlefields of the Great War, alongside the millions of soldiers and victims, was the founding hope that happiness on earth could be achieved through reason. The Second World War reinforced this disillusion. Critics realised that reason had done a deadly job by allowing the multiplication of the powers of destruction and by powerfully contributing to the enslavement of peoples.

The Great War proved to moralists that science helps people to live, but can also be a cause of death. It provides the means by which to govern, but also by which to enslave, peoples. Moralists repeatedly asserted that science as such does not promote happiness because it is devoid of meaning.[9]

Similarly, the great European wars put an end to the conquest of the world by Western Europe. The best of us, with an awakened conscience, denounced the plundering of the Third World – as Conrad did in his fiction.[10]

The explosion of the first atomic bomb (6 August 1945) was the symbol of an inappropriate use of science and gave rise to numberless debates between scientists – Einstein's attitude on the subject is well known. Political analysts noted that the power of technology cannot replace the inspiration of a genuine political project.[11]

3.2 *The condemnation of utopias*

Among the great literary works of the century, many were anti-

---

[9] See as an illustration of this the writings of Georges Duhamel, a humanist doctor, e.g., *La Possession* du *Monde* (Paris, Gallimard, 1920).

[10] Especially in *The Heart of Darkness* (1899).

[11] See Raymond Aron, *The Disillusions of Progress*, (Paris, 1949).

utopias. Two of them are well known: *Brave New World* (translated into French as *Le Meilleur des Mondes*) by Aldous Huxley[12] and *Nineteen Eighty-Four* by George Orwell.[13] In these novels one can read the condemnation of those utopias which acted to establish modernism. The authors acknowledge that the world realised in compliance with such principles has become inhuman. Despotism is still there and it has become even more tyrannical. The oppression of the poor by the rich is even more absolute. Similarly, Kafka's works and the novels of the absurd as a metaphysical value are protests against the power of techno-science and an all-powerful administration.

These criticisms linked up with those produced by the victims of the economic and political system.[14] Such a reality contradicted the notion of an ideal natural state and made that of the Fall topically relevant again.[15]

3.3 *Reason in crisis*

The scientific method was condemned and criticised for falsifying the human experience. Religious circles were involved in a controversy against 'secularisation'. This kind of criticism involves a wish to rehabilite the sacred. Today's wild manifestations of the sacred also bear witness to such a reaction.[16]

Philosophers developed a philosophy which favoured subjectivity within a current of thought based on existence which makes freedom quite independent from material contingencies – a philosophy which distanced itself from the results of scientific investigation and considered them only from a utilitarian point of view.

This is to be found in the writings of the greatest philosophers of the century: Edmund Husserl and Martin Heidegger. The former, in a major

---

[12] *Brave New World (*Albatros Continental Library, 1947). One should not mistake Aldous for his grandfather Thomas Henry Huxley, who was the great populariser and defender of the theory of evolution. He was Darwin's friend and he supported a philosophy of nature from which the notion of finality was absent but which remained within the framework of deist thought. He was born in 1825 and died in 1895.

[13] A pseudonym for Eric Blair. *Nineteen Eighty-Four (*London, Secker & Warburg, 1965).

[14] On this point it is proper to note the contemporary relevance of Simone Weil's thought, particularly in *L'Enracinement* (Paris, Gallimard, 1949).

[15] See Ivan Gobry, *Procès de la culture. Mise en question chrétienne de la Culture (*Paris, Régnier, 1995).

[16] See Jacques Ellul, *Les Nouveaux Possédés (*Paris, Fayard, 1973).

work entitled *Die Krisis*,[17] started with the crisis in Europe, on the verge of a new war, and condemned scientific reductionism as the main source of the oblivion of values which alone could maintain civilisation.[18] Similarly, within the context of the collapse of Germany after the war, Heidegger saw in technology the triumph of practical reason and the dismissal of the question of being.[19]

The radical nature of these criticisms and the situation from which they sprang invite us to return to the foundations of modern culture. In a very particular way, it is our duty, within the framework of this Academy's activities, to consider one of the instruments of progress, the weapon which for better or worse has proved so efficient, that is to say, fundamental science and its technical applications. It is our duty to ask ourselves why it is so efficient – and at what cost. But we shall have to adopt a moderate approach, since no one should benefit from the progress of science on the one hand, and on the other hand treat it with contempt. It is not right to speak ill of what exists, for it is impossible not to acknowledge that we enjoy advantages which our ancestors did not have.

The question – it seems to me – is: how can we ensure everyone gains advantages from the good things which follow from the ascendency of man over nature? And this in a way that is comparable to what I tried to show is present in the Bible: how, from a singular situation (the kingdoms of David and of Solomon) a hope and a project grew up which involved the whole of mankind (represented by Adam, the human archetype).

III. Science and Conscience

I suggest that we should return to Rabelais' famous formula: 'science without conscience is the ruin of our souls'.

This phrase is useful because it prevents us from falling into two extremes, those of excluding or despising what exists. Science, it seems to me, should be recognised for what it is. In order to do that, one should bear its limits – which derive from its specialisation and abstraction – in mind. One should also consider that science only progresses because it

---

[17] The complete title is *Die Krisis der Europaischen Wissenschaften und die transzendentale Phänomenologie* (1935).

[18] The theme has been developed by modern phenomenology. See, for example, Michel Henry, *La Barbarie* (Paris, Gallimard, 1995).

[19] This is a recurrent theme found in *Was heisst denken?* (1954).

has been preceded by a specific project and is sustained by a fundamental desire for happiness.

1. *Science has Lost its Sacred Aura*

Science remains a source of hope that happiness can be achieved because it is capable of eradicating a number of scourges. But its successes created an illusion: the belief that all problems could be solved and that – short of vanquishing death – it would be possible to change man. On the eve of the new millennium, the lesson which history teaches us is that we should not sacralise science. Pascal said that 'even truth itself can become an idol'.[20]

It would be a mistake to lapse into what the Bible condemns as being idolatry, i.e the fact of worshipping one's own creation, or in other words, the fact of considering what is merely a means as an absolute.

Such an approach allows one to examine justly and fairly the new powers of science over human life, and not to jump to conclusions which either approve or condemn everything. The technical means of communication and information, remedies for sterility and methods of birth control, gene therapies, the achievement of longevity and the treatment of pain, the organisation of work, the management of agricultural resources, genetics – all these should be considered as instruments to an end. The power gained over nature is not the same thing as the use that is made of it. This is something which implies a moral responsibility, the principles of which are not provided by science. 'Science without conscience is the ruin of the soul' said Rabelais.

2. *A Sensible Approach*

The best attitude is – as the French say – 'to be reasonable' about it, i.e. to use one's reason and avoid extreme interpretations.

The value of science comes from the use of reason and this characterises human behaviour.

Although reason does not entirely command thought and the exercise of intelligence, it is important for us not to depreciate it. The return of the irrational is a snare.

---

[20] 'Truth itself can be made an idol of, because truth without charity is not God, but an image of God which must be neither loved nor adored – far less should its opposite, untruth, be loved or adored', *Les Pensées* (Paris, Gallimard (La Pléiade), 2000), p. 861.

To be reasonable about it, means to acknowledge that reason does not cover the whole of thought. Human thought is intuition, imagination, expectation, judgment, contemplation and inspiration. It is not only deductive, or a logical arrangement.

Thus science rests on elements (principles and intuitions) which are external to it and on which it is dependent. Science, which is a work of reason, also involves the other activities of intelligence. There are in science itself essential elements which do not fall within the province of objectivising reason. There are – as has already been said – elementary principles which resort to intuition, to convictions, as to the value of intelligence and its ability to reach the innermost reality of things, and finally to representations which have a symbolic dimension.

This is why the fundamental desires conveyed by the Messianic hope keep on living in mankind. Science rests on them in order to progress. It is therefore suitable to take them into consideration according to their motivations, to express a desire for happiness, and to allow it to realise itself.

3. *Science as a Source of Liberation*

All scientists know that science is based on research, which implies a climate of freedom. Science is today a source of hope in the future because it is connected with freedom of thought. A creative freedom, a founding freedom. Freedom in research, freedom in the formulation of theories, freedom in the refusal of certain approaches which are conducive to death.

In that sense, science is at one with the first meaning of the word 'Messianism' – 'to bring freedom'. Life is the best thing we possess. Life is not only a work of reason. The life of man involves both his body and his soul. The condemnation of 'modernism' invites us not to forget the fundamental dimension of mankind – the living soul. Every human being is a creature of desire. He is such because he is a creature endowed with speech. He feeds on the received word, on the given word, on a word which is bound up with the mystery of the Covenant, and with relating to others.

Thus is met the exacting demand of justice, which is part of the Messianic call.

CONCLUSION

It would seem that if the future is to be a future of happiness for everyone, it is important to return to the meaning of the word 'Messianism'. If we are to accept it, the promised horizon is not an abstract one. It is centered on the figure of the Messiah. Now the Messiah – in Greek: *Christos*, Christ – is a man.

Therefore man is the measure of the world. Man is the measure of everything that exists. Man is on the horizon of every creative act. The Christian faith provides us in Jesus with a figure of man which is identical with the eschatological person, the Son of Man, whose Second Coming the Christians await. The human reference prevents Messianism from being reduced to millenarianism.

The place for happiness is not a heavenly garden, or an enchanted island, or a city built harmoniously, or anything that man can dream of. Happiness is a happy, peaceful relationship with oneself, with others, above all with one's neighbours. Happiness is that sort of relationship with God that transfigures the present. The place for happiness is not another world, located in some indeterminate beyond, but a world of others, immediately to be experienced, centred on beaming love, founded on the word, on reciprocal trust and respect. The scientific community plays in this world a prominent role. To conclude, allow me to quote a passage from the Gospel. Jesus is evoking a last judgment scenario. As the Messiah, he says to the just:

> 'For I was hungry, and ye gave me meat; I was thirsty, and ye gave me drink; I was a stranger, and ye took me in; naked, and ye clothed me; I was sick, and ye visited me; I was in prison, and ye came unto me' (Mt 25, 35-45).

This addresses all nations. It concerns the whole of mankind, for the situation under discussion is that of every human being when he comes into this world. A new-born babe dies, if he is not fed with milk, clad, taken care of, and welcomed into this world with words that give a meaning to his life. This is how we should consider our lives, our searchings, our cares – with reference to such achievements.

At the beginning of this new millennium, let us rejoice that science enables us to make our contribution to this task, without excluding any one, and in a decisive way.

CREATION AND SCIENCE

WILLIAM E. CARROLL

During the past decade the Vatican Observatory and the Center for Theology and the Natural Sciences in Berkeley, California, have been sponsoring a series of conferences on what they call "scientific perspectives on divine action," which have resulted in the publication of four impressive volumes.[1] What has emerged as a major theme in the contributions of many of the scholars in these volumes is how contemporary science points to a kind of metaphysical space which can allow for divine agency in the world.[2] Thus, for example, the fascination with quantum mechanics and chaos theory, since each has been viewed as providing the metaphysical indeterminacy needed to provide an arena in which God can act.

For many theologians, the value of developments in contemporary science concerns what they perceive to be a fundamental difference from the view of the universe as a causally closed system operating according to the prescriptions of Newtonian mechanics. So long as the universe was seen in Newtonian terms, it was easy, so such an interpretation suggests, to limit divine action to an initial act of creation. Even the notion of God's continual causing of the existence of things was thought to be challenged by the principle of inertia, which seemed to entail the view that the universe was self-sufficient and thus required no appeal outside of itself, once it existed, to account for all motion and change.[3] According to these theologians, the deterministic view of the universe, made famous by Pierre Laplace, has

---

[1] *Quantum Cosmology and the Laws of Nature* (1993); *Chaos and Complexity* (1995); *Evolutionary and Molecular Biology* (1998); and *Neurosciences and the Person* (1999)

[2] This is a correlative to the need for a similar metaphysical space which allows for the causal agency of creatures.

[3] This view has been set forth by Hans Blumenberg, *The Legitimacy of the Modern Age*, translated by Robert Wallace (Cambridge, MA: MIT Press, 1971) and Wolfhart

been overturned by quantum indeterminism, and, as a result, God could be thought of as acting at the quantum level. Recently some theologians have argued that quantum mechanics allows us to think of divine action as the "providential determination of otherwise undetermined events." God's "governance at the quantum level consists in activating or actualizing one or another of the quantum entity's innate powers at particular instants." In an essay which applies such views to the field of genetics, Robert J. Russell adopts "the *theological* view that God's special action can be considered as objective and non-interventionist if the quantum events underlying genetic mutations are given an indeterminist interpretation philosophically. If it can be shown scientifically that quantum mechanics plays a role in genetic mutations, then by extension it can be claimed theologically that God's action in genetic mutations is a form of objectively special, non-interventionist divine action. Moreover, since genetics plays a key role in biological evolution, we can argue by inference that God's action plays a key role in biological evolution..."[4]

The British physicist and theologian, John Polkinghorne, although critical of the appeal to quantum indeterminacy as a way to make room for divine action in the world, does think that contemporary chaos theory offers a fruitful avenue for theological reflection. "The most obvious thing to say about chaotic systems is that they are intrinsically unpredictable. Their exquisite sensitivity means that we can never know enough to be able to predict with any long-term reliability how they will behave." Polkinghorne argues that the epistemological limitations which chaos theory presents point to a fundamental feature of the world, what he calls an "ontological openness."[5]

Pannenberg, *Toward a Theology of Nature*, translated by Ted Peters (Louisville, KY: Westminster/John Know Press, 1993) and in *Metaphysics and the Idea of God*, translated by Philip Clayton (Grand Rapids, MI: W. B. Eerdmans, 1990). For a discussion of these claims – especially how to understand the principle of inertia – see William E. Carroll, "The Scientific Revolution and Contemporary Discourse on Faith and Reason," in *Faith and Reason*, edited by Timothy Smith (St. Augustine's Press), forthcoming.

[4] Russell, thus, presents a sophisticated form of theistic evolution. Robert J. Russell, "Special Providence and Genetic Mutation: A New Defense of Theistic Evolution," in *Evolutionary and Molecular Biology: Scientific Perspectives on Divine Action*, edited by Robert J. Russell, William R. Stoeger, and Francisco J. Ayala, pp. 191-223, at p. 213 and p. 206, italics in original (Vatican City: Vatican Observatory Publications, 1998). Russell provides an excellent summary of the views of two theologians, Nancey Murphy and Thomas Tracy, on the general theological significance of quantum indeterminismon. p. 214.

[5] "I want to say that the physical world is open in its process, that the future is not just a tautologous spelling-out of what was already implicit in the past, but there is gen-

For Polkinghorne, chaos theory presents us with the possibility of “a metaphysically attractive option of openness, a causal grid from below which delineates an envelope of possibility...within which there remains room for manoeuvre.”[6] This “room for manoeuvre,” can be seen, according to Polkinghorne, in the act of creation itself, understood as: “...a kenosis (emptying) of divine omnipotence, which allows for something other than God to exist...”[7] Recently, Polkinghorne has written: “The act of creation involves a voluntary limitation, not only of divine power in allowing the other to be, but also of divine knowledge in allowing the future to be open... An evolutionary universe is to be understood theologically as one that is allowed by God, within certain limits, to make itself by exploring and realizing its own inherent fruitfulness. The gift of creaturely freedom is costly, for it carries with it the precariousness inherent in the self-restriction of divine control.”[8]

---

uine novelty, genuine becoming, in the history of the universe... The dead hand of the Laplacean Calculator is relaxed and there is scope for forms of causality other than the energetic transactions of current physical theory. As we shall see there is room for the operation of holistic organizing principles (presently unknown to us, but in principle open to scientific discernment), for human intentionality, and for divine providential interaction.” J. Polkinghorne, “The Laws of Nature and the Laws of Physics,” in *Quantum Cosmology and the Laws of Nature,* edited by Robert J. Russell, Nancey Murphy, and C.J. Isham (Vatican City: Vatican Observatory Publications, 1993), pp. 441-2.

[6] “How that manoeuvre is executed will depend upon other organizing principles, active in the situation, viewed holistically. A chaotic system faces a future of labyrinthine possibilities, which it will thread its way through according to the indiscernible effects of infinitesimal triggers, nudging it this way or that...[C]haos theory [is] actually an approximation to a more supple reality, these triggers of vanishingly small energy input become non-energetic items of information input (“this way”, “that way”) as proliferating possibilities are negotiated. The way the envelope of possibility is actually traversed will depend upon *downward causation* by such information input, for whose operation it affords the necessary room for manoeuvre.” *Ibid.*, p. 443.

[7] “I am suggesting that we need to go further and recognize that the act of creating the other in its freedom involves also a kenosis of the divine omniscience. God continues to know all that can be known, possessing what philosophers call a current omniscience, but God does not possess an absolute omniscience, for God allows the future to be truly open. I do not think that this negates the Christian hope of ultimate eschatological fulfillment. God may be held to bring about such determinate purpose even if it is by way of contingent paths.” *ibid.*, pp. 447-8. On this final point see D. Bartholomew, *God of Chance* (London: SCM Press, 1984).

[8] John Polkinghorne, “Chaos Theory and Divine Action,” in *Religion and Science*, edited by W. Mark Richardson and Wesley J. Wildman (New York: Routledge, 1996), pp. 250 and 249.

I think that Polkinghorne moves far too easily from claims in epistemology to claims in metaphysics. Various attempts by Polkinghorne, Arthur Peacocke, Nancey Murphy, George Ellis,[9] and others to locate a venue for divine agency in the indeterminism of contemporary physics really amount to the contention that any account of the physical world in the natural sciences is somehow inherently incomplete. In other words, these authors must maintain that the natural sciences cannot in principle provide a complete, coherent scientific account of physical reality.[10]

I do not want to address the complex questions of how properly to interpret quantum mechanics or chaos theory.[11] What I should like to focus on

---

[9] See their essays in *Chaos and Complexity*, edited by Robert J. Russell, Nancey Murphy, and Arthur Peacocke (Vatican City: Vatican Observatory Publications, 1995).

[10] This is a criticism aptly made by Willem B. Drees in "Gaps for God?" in *Chaos and Complexity, op. cit.*, pp. 223-237. That Polkinghorne is particularly susceptible to this criticism can be seen in the following observation he makes in this same volume: "For a chaotic system, its strange attractor represents the envelope of possibility within which its future motion will be contained. The infinitely variable paths of exploration of this strange attractor are not discriminated from each other by differences of energy. They represent different patterns of behavior, different unfoldings of temporal development. In a conventional interpretation of classical chaos theory, these different patterns of possibility are brought about by sensitive responses to infinitesimal disturbances of the system. Our metaphysical proposal replaces these physical nudges by a causal agency operating in the openness represented by the range of possible behaviors contained within the monoenergetic strange attractor. What was previously seen as the limit of predictability now represents a 'gap' within which other forms of causality can be at work." Polkinghorne, "The Metaphysics of Divine Action," in *Chaos and Complexity...*, pp. 153-4.

[11] The philosophical issues connected to a proper interpretation of quantum mechanics and chaos theory are extraordinarily complex. Robert J. Russell and Wesley J. Wildman ["Chaos: A Mathematical Introduction with Philosophical Reflections," in *Chaos and Complexity..., op. cit.*, pp. 49-90], for example, have argued persuasively that it is philosophically dangerous to move from the essentially mathematical realm of chaos theory to reach conclusions about metaphysical determinism or indeterminism; nor ought one to equate unpredictability with indeterminism. They note the use made by chaos theory in some theological circles: "The development of chaos theory has been welcomed by some theologians as powerful evidence that the universe is metaphysically open (i.e., not completely deterministic) at the macro-level. Metaphysical indeterminacy at the quantum level does not even need to be assumed, on this view, for chaos theory makes room for human freedom and divine acts in history that work wholly within nature's metaphysical openness and do not violate natural laws...[Such an interpretation is] without justification...since it makes little sense to appeal to chaos theory as positive evidence for metaphysical indeterminism when chaos theory is itself so useful for strengthening the hypothesis of metaphysical determinism: it provides a powerful way for determinists to argue that many kinds of apparent randomness in nature should be subsumed under deterministic covering laws." *Ibid.*, pp. 84 and 86.

is the concern for metaphysical space which informs the arguments of so many contemporary writers on science and theology, and to show how a return to Thomas Aquinas' discussion of creation[12] is particularly fruitful, especially his understanding of how God is the complete cause of the whole reality of whatever is and yet in the created world there is a rich array of real secondary causes.[13] God's creative act, for Aquinas, is not an example of divine withdrawal[14] but is, rather, the exercise of divine omnipotence. Furthermore, Aquinas' understanding of creation affirms the integrity and relative autonomy of the physical world and the adequacy of the natural sciences themselves to describe this world. In the thirteenth century, as a result of the translations into Latin of the works of Aristotle and his Muslim commentators, scholars of the caliber of Albert the Great and Thomas Aquinas wrestled with the implications for Christian theology of the most advanced science of their day. Following in the tradition of Muslim and Jewish thinkers, Thomas Aquinas developed an analysis of the doctrine of creation from nothing which remains one of the enduring accomplishments of Western culture. An examination of what he says about creation provides a refreshing clarity for discussions in our own day of the relationship between science and religion.[15]

It seemed to many of Aquinas' contemporaries that there was a fundamental incompatibility between the claim of ancient physics that something cannot come from nothing and the affirmation of Christian faith that God did produce everything from nothing. Furthermore, for the Greeks, since something must come from something, there must always be something – the universe must be eternal.

An eternal universe seemed to be incompatible with a universe created out of nothing, and so some mediaeval Christians thought that Greek sci-

---

[12] For a discussion of Aquinas' analysis of creation, see Steven E. Baldner and William E. Carroll, *Aquinas on Creation* (Toronto: Pontifical Institute of Mediaeval Studies, 1997). See also: William E. Carroll, "Aquinas and the Metaphysical Foundations of Modern Science," *Sapientia* 54 (1999), pp. 69-91.

[13] Too often, those who examine the distinction Aquinas draws between primary and secondary causality read Aquinas in the light of a Humean understanding of cause. See William A. Wallace, *Causality and Scientific Explanation*, 2 vols. (Ann Arbor: The University of Michigan Press, 1972), and Joseph De Finance, *Conoscenza dell'essere*, translated by M. Delmirani (Roma: Editrice Pontificia Università Gregoriana, 1993), pp. 332-423.

[14] This is what Polkinghorne calls "a kenosis (or emptying) of divine omnipotence."

[15] See William E. Carroll, "Thomas Aquinas and Big Bang Cosmology," *Sapientia* 53 (1998), pp. 74-95.

ence, especially in the person of Aristotle, ought to be banned, since it contradicted the truths of revelation. Aquinas, recognizing that the truths of science and the truths of faith could not contradict one another, since God is the author of all truth, went to work to reconcile the truths of Aristotelian science and Christian revelation.

The key to Aquinas' analysis is the distinction he draws between creation and change. The natural sciences, whether Aristotelian or those of our own day, have as their subject the world of changing things: from sub-atomic particles to acorns to galaxies. Whenever there is a change there must be something which changes. The Greeks are right: from nothing, nothing comes; that is, if the verb "to come" means a change. All change requires an underlying material reality.

Creating, on the other hand, is the radical causing of the whole existence of whatever exists. To cause completely something to exist is not to produce a change in something, is not to work on or with some already existing material. If there were a prior something which was used in the act of producing a new thing, the agent doing the producing would not be the *complete* cause of the new thing. But such a complete causing is precisely what the act of creation is. To create is to give existence, and all things are totally dependent upon God for the fact that they are. Creation out of nothing does not mean that God takes nothing and makes something out of "it." Rather, anything left entirely to itself, separated from the cause of its existence, would be absolutely nothing. To speak of creation out of nothing is simply to deny that there is any material cause in creation. Creation is not exclusively, nor even fundamentally, some distant event; it is the continuing, complete causing of the existence of whatever is. Creation, thus, is a subject for metaphysics and theology, not for the natural sciences.

Thomas Aquinas saw no contradiction in the notion of an eternal created universe. For, even if the universe had no temporal beginning, it still would depend upon God for its very being. There is no conflict between the doctrine of creation and any physical theory. Theories in the natural sciences account for change. Whether the changes described are biological or cosmological, unending or finite, they remain processes. Creation accounts for the existence of things, not for changes in things.

Aquinas thought that reason alone, in the discipline of metaphysics, could prove that the universe is created: that it is dependent upon God for its existence. The metaphysical understanding of creation leaves open the question of an absolute temporal beginning of the universe. Aquinas thought that neither metaphysics nor the natural sciences could determine conclusively whether or not the universe is temporally finite. He accepted the temporal finitude of the universe only as a matter of faith. Here we have an excellent example of what Aquinas would call faith's adding to or perfecting what reason knows.

Although God is the immediate cause of all existing things, creatures are still true causes of effects. Aquinas' explanation is that creatures are the true causes of whatever comes to be either through motion or generation and that God is the cause of the being of all things, even of that which is produced through motion or generation. God is the constant cause of all being; creatures cause, as it were, only the determinations of being.

The natural sciences seek to discover real causes in the world. Aquinas argues that a doctrine of creation out of nothing, which affirms the radical dependence of all being upon God as its cause, is fully compatible with the discovery of causes in nature. God's omnipotence does not challenge the possibility of real causality for creatures, including that particular causality, free will, which is characteristic of human beings. Aquinas would reject any notion of a divine withdrawal from the world so as to leave room (a metaphysical space) for the action of creatures in such a way, for example, that God would be said to allow or to permit creaturely causality. Aquinas would also reject a process theology which denies God's immutability and His omnipotence (as well as His knowledge of the future) so that God would be said to be evolving or changing along with the universe and everything in it. For Aquinas, both views fail to do justice either to God or to creation. Creatures are, and are what they are (including those which are free), precisely because God is present to them as cause. Were God to withdraw, all that exists would cease to be. Creaturely freedom and the integrity of nature, in general, are guaranteed by God's creative causality, i.e., by God's intimate presence in all that He creates. Here is how Aquinas expresses it in the *Summa theologiae*:

> Some have understood God to work in every agent in such a way that no created power has any effect in things, but that God alone is the ultimate cause of everything wrought; for instance, that it is not fire that gives heat, but God in the fire, and so forth. But this is impossible. First, because the order of cause and effect would be taken away from created things, and this would imply lack of power in the Creator, for it is due to the power of the cause, that it bestows active power on its effect. Secondly, because the active powers which are seen to exist in things, would be bestowed on things to no purpose, if these wrought nothing through them. Indeed, all things

> created would seem, in a way, to be purposeless, if they lacked an operation proper to them, since the purpose of everything is its operation...We must therefore understand that God works in things in such a manner that things have their proper operation...[16]

As Simon Tugwell aptly puts it: "The fact that things exist and act in their own right is the most telling indication that God is existing and acting in them."[17] For God to be universal cause of being does not mean that God only provides what is common to being and thus allows secondary causes *by themselves* to provide the particular determinations of individual beings.[18]

---

[16] *Summa theologiae* I, q. 105, a. 5. In his earliest reference to this topic, Aquinas writes: "God is also the cause of these things, operating more intimately in them than do the other causes that involve motion, because He Himself gives being to things. The other causes, in contrast, are the causes that, as it were, specify that being. The entire being of any thing cannot come from some creature, since matter is from God alone. Being, however, is more intimate to anything than those things by which being is specified. Hence, it [being] remains even if those other things are removed, as is said in the *Book of Causes*, proposition 1. Hence, the operation of the Creator pertains more to what is intimate in a thing than does the operation of any secondary causes. The fact, therefore, that a creature is the cause of some other creature does not preclude that God operate immediately in all things, insofar as His power is like an intermediary that joins the power of any secondary cause with its effect. In fact, the power of a creature cannot achieve its effect except by the power of the Creator, from whom is all power, preservation of power, and order [of cause] to effect. For this reason, as is said in the same place of the *Book of Causes*, the causality of the secondary cause is rooted in the causality of the primary cause." *In II Sent.*, d. 1, q. 1, a. 4, resp. We ought to note that in the passage from the *Summa theologiae* Aquinas' distinction between primary and secondary causality concerns formal and final causality as well as efficient causality.

[17] Simon Tugwell, *Albert and Aquinas: Selected Writings* (New York: The Paulist Press, 1988), p. 213.

[18] See Cornelio Fabro, *Participation et causalité selon S. Thomas d'Aquin* (Louvain-Paris: Nauwelarts, 1961), pp. 507ff. The alleged incompatibility between divine omnipotence and creaturely causality is the result, at least in part, of the failure to understand divine transcendence. Process theologians attack classical Christian theism "for its picture of a distant, lordly deity, incapable of being affected by the things of the world, standing at the summit of metaphysical hierarchies, and reinforcing their oppressive structures." They "tend to define the issues in terms of a debate between rival metaphysical systems, with the utterly transcendent, omnipotent God of classical theism set against the more immanent, collaborative God of process thought, who is (for Whitehead) an actual occasion or (for Hartshorne, Ogden, Cobb, and Griffin) a society of actual occasions, but at any rate one of the things in the world in genuine interaction with the others." William Placher, *The Domestication of Transcendence* (Louisville, KY: Westminster Press, 1996), pp. 1 and 9.

Proponents of what has been termed "panentheism" criticize "classical Western the-

In our own day, various intellectual schemes which seek to make room for the agency of creatures or which find theological significance for divine action in terms of the "ontological openness" of quantum mechanics and chaos theory fail to recognize the profound metaphysical point that divine causality transcends any other category of causality.

When Aquinas speaks of causality he employs a much richer sense of the term than we tend to use today. Whereas contemporary thinkers have come to view causality in terms of a kind of "necessary consequentiality" between events, Aquinas understood causality in terms of metaphysical dependence.[19] As part of the philosophy of nature connected to the rise of "modern science," two of the four causes of Aristotelian science, the final and the formal, were considered irrelevant. Furthermore, to the extent that the natural sciences came to be seen as depending exclusively on the language of mathematics, only that which was measurable would fall within their explanatory domains.[20]

Even the notion of agent or efficient causality underwent a profound change from the Aristotelian sense. It was conceived "exclusively in terms

---

ism" for understanding the world as being "ontologically outside of God," and, thus, as presenting significant difficulties for making sense of God's action in the world. [P. Clayton, *God and Contemporary Science* (Edinburgh: Edinburgh University Press, 1997), p. 100.] Their concern is to fashion a theology consistent with biblical revelation and the insights of contemporary science and philosophy, but their criticism of classical theism does not do justice to the position of Aquinas.

[19] "Il titolo di questo libro richiama una nozione, 'causa,' che suggerisce al lettore contemporaneo contenuti concettuali per qualche aspetto sostanzialmente diversi da quelli che evocava nel lettore medievale. Difatti per i contemporanei il termine 'causa' indica per lo più la sola idea di consequenzialità necessaria...Per il lettore medievale, invece, accanto all'idea di una connessione di fatto, il concetto di 'causa' trasmette quella di un ordinamento metafisico...La causa, in questo modo, è superiore all'effetto; e poiché è principio della sua sussistenza in essere, è principio anche della sua intelligibilità." Cristina D'Ancona Costa, "Introduzione," in Tommaso D'Aquino, *Commento al Libro delle Cause* (Milan: Rusconi, 1986), p. 7.

[20] Mario Bunge points out the important role that empirical science has played in this shift in our understanding of causality: "The Aristotelian teaching of causes lasted in the official Western culture until the Renaissance. When modern science was born, formal and final causes were left aside as standing beyond the reach of experiment; and material causes were taken for granted in connection with all natural happenings... Hence, of the four Aristotelian causes only the efficient cause was regarded as worthy of scientific research." Mario Bunge, *Causality and Modern Science* (New York: Dover, 1979), p. 32. See William A. Wallace, O.P., *Causality and Scientific Explanation*, 2 vols. (Ann Arbor: University of Michigan Press, 1972), vol. 2, p. 246.

of the force or energy that moved the fundamental parts of the universe."[21] In the eighteenth century, David Hume called into question even this narrow idea of efficient causality. Since the supposed influence of a cause upon its effect was not directly evident to sense observation, Hume concluded that the connection between cause and effect was not a feature of the real world, "but only a habit of our thinking as we become accustomed to see one thing constantly conjoined to another." Causality became not a property of things but of thought; it "was no longer an *ontological* reality in the world outside ourselves, but an *epistemological* property of the way we think about the world. [Thus,] the hallmark of causality was found in the epistemological category of *predictability* rather than the ontological category of *dependence*."[22]

One of the consequences of viewing causality *exclusively* in terms of a physical force is that divine causality, too, comes to be seen in such terms.[23] To conceive God's causality in this way is to make God a kind of competing cause in the world. To view the world as functioning in terms of an ordered regularity of mechanical causes seemed to mean that there was no room for any kind of special divine action.[24] Starting from this kind

---

[21] Michael J. Dodds, "The Doctrine of Causality in Aquinas and *The Book of Causes*: One Key to Understanding the Nature of Divine Action," paper delivered at the Thomistic Institute, University of Notre Dame, July 2000. I am grateful to Professor Dodds for his analysis of the narrowing of the notion of causality, which I have used in this section of my paper.

[22] *Ibid.*

[23] As Philip Clayton has observed: "The present-day crisis in the notion of divine action has resulted as much as anything from a shift in the notion of causality." *God and Contemporary Science, op. cit.*, p. 189.

[24] "The more man is imbued with the ordered regularity of all events the firmer becomes his conviction that there is no room left by the side of this ordered regularity for causes of a different nature. For him neither the rule of human nor the rule of divine will exists as an independent cause of natural events." Albert Einstein, *Out of my Later Years* (New York: Wisdom Library, 1950), p. 32. Keith Ward also observes: "The scientific world-view seems to leave no room for God to act, since everything that happens is determined by scientific laws." Keith Ward, *Divine Action* (London: Collins, 1990), p. l. Langdon Gilkey explains this reluctance of contemporary theologians to speak of divine intervention: "Thus contemporary theology does not expect, nor does it speak of, wondrous divine events on the surface of natural and historical life. The causal nexus in space and time which Enlightenment science and philosophy introduced into the Western mind and which was assumed by liberalism is also assumed by modern theologians and scholars; since they participate in the modern world of science both intellectually and existentially, they can scarcely do anything else." Langdon Gilkey, "Cosmology, Ontology and the Travail of Biblical Language," in Owen C. Thomas, ed.,

of analysis, several contemporary theologians, as we have seen, have found such room for divine action, what Polkinghorne calls "room for divine manoeuvre," in the new scientific view of the world set forth in quantum mechanics and chaos theory.

In various contemporary accounts of divine action there is a special concern to locate the "causal joint," that particular point or way that divine causality can be conceived of as interfacing with the physical world. The concern for finding such a "causal joint" proceeds from assumptions about divine causality which are problematic.[25] For even if we grant that contemporary physics affirms a radical indeterminism in nature, any analysis of God's action in the world will be impaired if we restrict our notion of cause to the categories of matter, energy, and force. It is important to note, however, that the narrowing of the notion of causality, in the thought of Hume and others, to which I have referred, has occurred in the philosophy of nature, not in the empirical sciences themselves. When scientists adopt such limited or restricted notions of cause, they are operating in a broader arena of analysis than that of the empirical sciences themselves. In a sense, natural philosophy is a more general science of nature than any of the specialized sciences; it examines topics such as the nature of change and time, the role of mathematics in the investigation of nature, and related questions.

God's Activity in the World: the Contemporary Problem (Chico, California: Scholar's Press, 1983), p. 31.

[25] As Philip Clayton explains, "If one is to offer a full theory of divine agency; one must include some account of where the 'causal joint' is at which God's action directly impacts on the world. To do this requires one in turn to get one's hands dirty with the actual scientific data and theories, including the basic features of relativity theory, quantum mechanics and (more recently) chaos theory." Philip Clayton, *God and Contemporary Science*, p. 192. The difficulties of discovering such a "causal joint," however, are evident in the work of Arthur Peacocke who maintains that "the continuing action of God with the world-as-a-whole might best be envisaged...as analogous to an input of information rather than of energy." The problem with this notion, as Peacocke recognizes, is that in physics "any input of information requires some input of matter/energy." Such matter/energy input on God's part, however, smacks of interference with the order of the world. Peacocke concludes that he has located, but not solved, the problem of the "causal joint": "How can God exert his influence on, make an input of information into, the world-as-a-whole without an input of matter/energy? This seems to me to be the ultimate level of the 'causal joint' conundrum, for it involves the very nature of the divine being in relation to that of matter/energy and seems to be the right place in which to locate the problem..." Arthur Peacocke, *Theology for a Scientific Age: Being and Becoming – Natural, Divine and Human* (Minneapolis, MN: Fortress Press, 1993), pp. 149-151, 160-161, 164.

One obstacle to a return to the rich view of causality found in the thought of Aquinas, including his profound understanding of the differences between the explanatory domains of creation and the natural sciences, is the view that his theological and philosophical thought is too closely tied to a science of nature which we reject as false. Interpretations of modernity depend in important ways on analyses of the Scientific Revolution of the seventeenth century. In particular, the materialism, mechanism, and reductionism so often associated with modern science has its roots in a faulty philosophy of nature supported by an interpretation of the history of science.[26] The understanding of the rise of modern science as involving a rejection of Aristotelian science[27] has led many to ignore the profound truths about nature, human nature, and God which are found in Aristotelian and Thomistic thought.

If there is a fundamental incompatibility, or incommensurability, between Aristotelian science and modern science, then any theological or philosophical reflection rooted in or employing principles from Aristotelian science must either be rejected or radically reformulated. Often I partici-

---

[26] Examples of such philosophical claims are readily evident in many texts. More than twenty-five years ago, the French biologist Jacques Monod remarked: “Anything can be reduced to simple, obvious, mechanical interactions. The cell is a machine; the animal is a machine; man is a machine.” (Jacques Monod, *Chance and Necessity: An Essay on the Natural Philosophy of Biology.* New York: Knopf, 1974, p. ix) Or consider the well-known comment by Richard Dawkins, author of *The Selfish Gene*, who claims that a human being is not a cause but an effect, and that life and mind are merely the outcome of genes that “swarm in huge colonies, safe inside gigantic lumbering robots.”(Richard Dawkins, *The Selfish Gene*, New York: Oxford University Press, 1976, p. 21) In *River Out of Eden: A Darwinian View of Life,* Dawkins is not afraid to draw the following conclusion: “The universe we observe has precisely the properties we should expect if there is, at bottom, no design, no purpose, no evil and no good, nothing but blind pitiless indifference...DNA neither knows nor cares. DNA just is. And we dance to its music.” (New York: Basic Books, 1995, p. 133). Sir Francis Crick, co-discoverer of the double-helix structure of the DNA molecule, writes at the beginning of *The Astonishing Hypothesis*: “The Astonishing Hypothesis is that ‘You,’ your joys and your sorrows, your memories and your ambitions, your sense of personal identity and your free will, are in fact no more than the behavior of a vast assembly of nerve cells and their associated molecules.” (New York: Scribner, 1994)

[27] The commonly accepted narrative of the Scientific Revolution sees a fundamental discontinuity in the history of science which heralds the birth of modern science. For an excellent survey of various interpretations of the Scientific Revolution, see H. Floris Cohen’s *The Scientific Revolution: A Historiographical Survey* (1994). David Lindberg’s introductory essay on conceptions of the Scientific Revolution in D. Lindberg and R. Westman (eds.), *Reappraisals of the Scientific Revolution* (1990) is also excellent.

pate in conferences on the relationship between religion and science in which speakers refer to the "Newtonian settlement" as the basis for modern philosophy and theology.[28] This "settlement" tends to rule out appeals to Aristotelian and Thomistic natural philosophy since, so the argument goes, such a philosophy of nature has been rendered false[29] by modern science. This helps to explain why in the seventeenth and eighteenth centuries it was apparent to many that *only* a mechanistic philosophy of nature could meet the evidence of modern science.[30] More frequently today process thought is urged as providing the necessary philosophical complement to the natural sciences. Form and matter, substance and accident, teleology, and the like (concepts which are at the heart of Thomistic natural philosophy) are thus all seen as part of a view of the world which, thanks to the Scientific Revolution, we know is wrong.

An elaborate analysis of the Scientific Revolution, especially an investigation of questions of continuity and discontinuity in developments in the natural sciences in this period is well beyond the scope of this essay. Here I can only sketch in outline a way to look at the developments in science at the dawn of the modern age which does not involve a radical break with the past. The tremendous advances in the role of mathematics in the study of nature, characteristic of the Scientific Revolution, do not require, I think, a rejection of Aristotelian and Thomistic natural philosophy. Thomas Aquinas, following Aristotle, distinguishes between the natural sciences and mathematics in terms of their objects of study as well as in terms of the different ways in which these objects are known. The natural sciences study what exists in matter and in motion *precisely* as these things exist in matter and motion. Man cannot be studied, as man, distinct from flesh and bones. Man cannot be understood without his materiality. Mathematics studies those dimensions and quantities which *exist* in sensible matter, but which can be *known* separate from sensible matter. Man, through a special process of intellectual abstraction,

---

[28] It is important to note that those who speak of such a "settlement" also argue that contemporary science, especially relativity theory and quantum mechanics, have altered this settlement so radically that theologians and philosophers must adjust their understanding of nature, human nature, and God to take into consideration the new scientific perspective(s).

[29] For those who dislike the notion of "truth" and "falsity" in discussions of claims about the world, the argument is simply that a new paradigm has replaced an old one.

[30] Indeed, early proponents of mechanism, especially in the seventeenth century, saw in it a way to reconcile their belief in God with the insights of Newtonian science.

has the capacity to understand shapes and numbers independently from the material bodies in which they exist.[31]

For Aquinas, mathematics does not provide a *deeper* explanation of the world of nature than do the natural sciences; nor does mathematics provide the true principles of scientific inquiry for the natural sciences. The natural sciences have an autonomy appropriately their own.[32]

According to Aquinas, although mathematics and the natural sciences are autonomous and distinct sciences, one may apply mathematical principles to the study of natural phenomena. Such applications occur in neither the science of mathematics, nor in physics. They constitute mixed sciences: types of knowledge that are intermediate between what we today might term "pure" mathematics and a more general science of nature.[33] Referring to such a mixed science, Aquinas writes: "it does not belong to the mathematician to treat of motion, although mathematical principles can be applied to motion...The measurements of motions are studies in the intermediate sciences between mathematics and natural science."[34]

---

[31] Aquinas' most important work in this respect can be found in his *Commentary on Boethius' 'On the Trinity'* (questions 4 and 5) and in his commentary on the second book of Aristotle's *Physics*.

[32] The importance of mathematics in the thought of Galileo and Newton has led some scholars such as E. A. Burtt and Alexandre Koyré to see the Scientific Revolution as a radical shift in metaphysics: a return, if you will, to the heritage of Plato and a rejection of Aristotle. Such an interpretation misses an important point in the mediaeval understanding of the relationship between mathematics and physics.

[33] Aristotle, in the second book of the *Physics*, recognizes the legitimacy of such intermediate sciences, what he considers to be *in some sense* branches of mathematics which come nearest to the study of nature: optics, harmonics, and astronomy.

[34] *Commentary on Boethius' 'On the Trinity'* q. 5, a. 3, ad 5 [*The Division and Methods of the Sciences*, translated by Armand Maurer (Pontifical Institute of Mediaeval Studies, 1963), p. 36.] See also, *In II Phys.* lec. 3, n. 8. "So there are three levels of sciences concerning natural and mathematical entities. Some are purely natural and treat of the properties of natural things as such, like physics...Others are purely mathematical and treat of quantities absolutely, as geometry considers magnitude and arithmetic number. Still others are intermediate, and these apply mathematical principles to natural things; for instance, music, astronomy, and the like. These sciences, however, have a closer affinity to mathematics, because in their thinking that which is physical is, as it were, material, whereas that which is mathematical is, as it were, formal. For example, music considers sounds, not inasmuch as they are sounds, but inasmuch as they are proportionable according to numbers; and the same holds in other sciences. Thus they demonstrate their conclusions concerning natural things, but by means of mathematics." (Maurer, pp. 37-38). For an insightful discussion of this treatise, see Stephen L. Brock, "Autonomia e gerarchia delle scienze in Tommaso d'Aquino. La difficoltà dellla sapien-

The application of mathematical principles to the study of natural phenomena is never a substitute for the natural sciences themselves which have as their object the study of physical bodies in their full reality. Principles of mathematics, although applicable to the study of natural phenomena, cannot explain the causes and true nature of natural phenomena.

It seems to me[35] that we can best understand the history of science in the fourteenth through the seventeenth centuries – and, indeed, beyond to our own time – if we recognize that some of the greatest accomplishments in the sciences have taken place in those intermediate sciences between mathematics and the natural sciences. The careful distinctions drawn by Thomas Aquinas frequently have been lost in the midst of the great advances such a mathematical approach has achieved.[36]

Once we understand the nature of mathematics, the natural sciences, and the intermediate sciences – an understanding present in the thought of Aristotle, and reaffirmed by Thomas Aquinas – then, I think, we can see a fundamental continuity in the history of science from the time of Aristotle to the present. Although ancient and mediaeval thinkers were not very concerned with the application of mathematics to the study of nature, still, they did recognize the validity of the use of mathematics in investigating nature. Such a perspective on the Scientific Revolution frees us from the false view that one must choose between Aristotle and the great advances of modern science.[37]

---

za," in *Unità e autonomia del sapere. Il dibattito del XIII secolo*, ed. Rafael Martínez , pp. 71-96 (Rome: Armando Editore, 1994).

[35] And here I am following in the footsteps of James Weisheipl, William Wallace, and others.

[36] The confusion is already in Descartes, who called inertia the first law of nature, rather than recognizing it, as Newton did, as a mathematical principle of natural philosophy.

[37] We would also be emancipated from the false exaggeration of the importance of mathematics, an exaggeration which has encouraged many to force all the sciences – natural and social – into the Procustean bed of mathematics, belittling or tending to ignore what cannot be timed, weighed, measured, or counted.

One of the great achievements of Albert the Great and Thomas Aquinas was their clear demonstration of the autonomy of the natural sciences: an autonomy, by the way, with respect to theology and to faith, as well as with respect to mathematics. They had no doubt that the physical universe is intelligible and that it is, therefore, an appropriate object of scientific investigation. The natural scientist explains change in its many forms: generation and destruction, locomotion, alteration, and the like. A science of generation and destruction, locomotion, and alteration must provide explanations in terms of the proper causes for these changes. The principles used in these explanations are not

The philosophical baggage of a mechanistic and materialistic natural philosophy which is often associated with modern science is the product of *philosophical* traditions in the seventeenth century and beyond. Mechanism and materialism represent a radical rejection of Aristotelian and Thomistic natural philosophy, but mechanism and materialism remain excess baggage, *not required* in order to accept the advances in our understanding of the world which are the legacy of Galileo and Newton. Although many historians, philosophers, and theologians see modern science as providing, ultimately, a challenge to the God of traditional religion, such a judgment rests on questionable interpretations of the Scientific Revolution as well as on a failure to appreciate the theological and philosophical heritage of the Middle Ages, according to which divine action does not challenge the appropriate causal autonomy of the natural world.

The point I wish to emphasize as a result of this brief excursion into the historiography of the Scientific Revolution is that particular views which embrace a radical discontinuity between "modern science" and Aristotelian and mediaeval science lead many to disregard or summarily to reject important insights into the nature of causality, divine and that of creatures, forged by thinkers such as Thomas Aquinas.

Misinterpretations of the Scientific Revolution may have also tempted some in the Thomistic tradition to retreat from the arena of natural philosophy to bask in the seemingly safer and ethereal realm of metaphysics. The history of science can help us distinguish among the advances of modern science, the mechanistic and materialist natural philosophy which has accompanied these advances, and the principles of Thomistic natural philosophy which still can lead to a deeper and more complete understanding of nature, human nature, and God.[38]

---

mathematical. And it does not matter whether we are speaking of productive, practical, or theoretical science. How can points, lines, surfaces, numbers, or equations – principles of mathematics – how can these cause the construction of houses or the writing of a poem? How can points, lines, surfaces, numbers or equations cause men to fashion constitutions, to engage in commerce or to live virtuously? How can points, lines, surfaces, numbers or equations cause the birth of an animal, the growth of an acorn into an oak tree, the movement of either planets or subatomic particles? As Albert and Thomas clearly understood, scientific explanations – explanations in terms of causes – employ the principles appropriate to each science. Although mathematics is clearer and more certain than the natural sciences, we must resist the temptation to regard mathematics either as the only true science or as a substitute for the natural sciences.

[38] Much work needs to be done by those in the Thomistic tradition to incorporate the discoveries of modern science into a broader philosophy of nature. Three authors

Thomas Aquinas' understanding of creation and divine causality allows us to avoid various contemporary attempts to accommodate the discoveries of the natural sciences by denying God's omnipotence, omniscience, and timelessness. Aquinas provides us as well with a robust view of divine action which does not require some form of metaphysical indeterminism in the world: an "ontological openness" so that God's acts might not "interfere" with nature. However impressive the advances in science which began in the seventeenth century, these advances do not challenge the fundamental insights about creation and science reached by Thomas Aquinas.

---

who have worked in this area are: Benedict Ashley, *Theologies of the Body*; Richard Connell, *Substance and Modern Science*; and William Wallace, *From a Realist Point of View* and *The Modeling of Nature*.

THE TRANSITION FROM BIOLOGICAL TO CULTURAL EVOLUTION

WOLF SINGER

Introduction

The emergence of culture is with all likelihood the result of synergistic interactions among several evolutionary events, the most important consisting of an evolutionary refinement of brain functions. The use of tools, the formation of labour-sharing societies, the management of agriculture, and the development of language are above all other factors consequences of the increasing sophistication of the cognitive functions and motor skills provided by the brain of homo sapiens sapiens. Because our direct ancestors are all extinct it is extremely difficult to infer which aspects of brain development were actually decisive for the transition from apes to early hominids and finally culture-competent sapiens-sapiens. The only truly longitudinal data on the evolution of the human brain come from studies of fossil skulls. These analyses reveal a gradual increase in brain volume – but this notion is not particularly helpful because brain size alone, even if considered in relation to body weight, is only a poor correlate of functional sophistication. Thus, inferences on evolutionary changes in brain organisation have to rely on comparison of species that escaped extinction. However, and this is both interesting and unfortunate for studies of evolution, the surviving species all bifurcated from the line of our ancestors long before the gap that separates us from our nearest relatives, the apes. Therefore, only rather indirect inferences are possible.

What Makes the Difference?

The first question which arises is whether our brains differ from those of our ancestors who initiated cultural evolution, painted the walls of their caves, and invented tools. The answer is yes and no. As far as genetically determined features are concerned, i.e. the molecular composition, the anatomical structures and the basic connectivity patterns, there cannot be any major differences because evolution is slow. This implies that our cave-dwelling ancestors were born with brains that must have had roughly the same inborn abilities as those of our babies. Hence, competences exceeding those of our ancestors must be attributed to the action of epigenetic factors, i.e. to experience-dependent modifications of postnatal brain development and to learning.

The two processes of epigenetic knowledge acquisition, experience dependent shaping of neuronal architectures during early development on the one hand, and learning on the other, differ at the neuronal level mainly with respect to the reversibility and the amplitude of the changes. Both are associated with lasting modifications of the interactions among neurons. During early development, experience can modify the architecture of neuronal connectivity by influencing the consolidation and disruption of newly formed pathways. Once these developmental processes decline, which is thought to occur around puberty, further modifications of functional architectures appear to be restricted to changes in the efficacy of the now consolidated repertoire of connections (see on this point Singer 1990, 1995). Thus, although the genetically determined blueprint of our brains is probably the same as that of our ancestors, our brains are likely to differ because of differences in the epigenetic shaping of fine structure.

This susceptibility of brain functions to undergoing epigenetic modifications is certainly a key factor in cultural evolution because it permits a highly efficient transmission of acquired abilities and knowledge from one generation to the next. It permits closure of the re-entry loop that couples collective achievements accomplished by interacting brains to the epigenetic shaping of ever more sophisticated functions of individual brains. Many of our cognitive abilities owe their differentiation to this collective learning process, and the reciprocity of the mechanism makes it difficult to determine which of our cognitive abilities have been the cause and which the result of cultural evolution. Despite this caveat our knowledge about the evolution of brains permits some educated guesses about which of the newly acquired neuronal functions might have actually triggered the onset of cultural evolution.

Concerning specific sensory or motor skills homo sapiens sapiens is a generalist. We perform reasonably well in many domains but for most of them one can identify animals that outperform us. Still, if one distributed points for performance in the various sensory modalities and for basic motor skills we would with all likelihood come out as winners. It is unlikely, however, that this superiority in average performance is alone sufficient to account for the emergence of culture. Rather, our culture competence seems to result from the evolutionary development of certain cognitive functions that are unique to humans. One of these is probably our ability to generate abstract, symbolic meta-representations of cognitive contents by subjecting the results of first order cognitive operations iteratively to further cognitive processing of a higher order. This competence requires the ability to identify relations among the numerous distributed cognitive processes and to represent these relations. The results of such an iteration of cognitive operations are modality invariant and hence abstract descriptions of the outcome of first order cognitive processes. As these higher order descriptions are equivalent with an internal protocol that keeps track of the brain's own cognitive operations, they can be considered as the substrate of our ability to be aware of our own sensations and intentions as well as those of others. This awareness, in turn, is probably at the origin of our unique ability to use a symbolic communication system and to generate a theory of mind. We seem to be the only species that is capable of imagining the thoughts and emotions of the respective other when she or he is in a particular situation. We are the only species capable of entering into dialogues of the format "I know that you know that I know", or "I know that you know how I feel". Such dialogues permit not only a deeper understanding of the respective other but they also allow one to experience one's own cognitive functions in the reflection of the perceptions of the other. Thus, the ability to generate a theory of mind has probably been instrumental in the development of social interactions that shape our self-concepts and provide the basis for the experience that we are autonomous agents endowed with intentionality and free will. We experience these cultural constructs to be as real as pre-cultural realities and hence these social realities are likely to have as important a role in the epigenetic shaping of brain functions as the other environmental factors. This has deep consequences as it implies that cultural embedding influences the fine grained architecture of brains and hence part of the phenotype of the organism. Thus, cultural evolution is no longer constrained, as is biological evolution, by the inability to translate experience gathered by preceding generations into modifications of the phenotype of the offspring.

Neuronal Prerequisites for the Emergence of Culture

What do we know about the neuronal substrate that enables human brains to run protocols and generate meta-representations of their own performance, to realise what one might call an 'inner eye' function and to develop a theory of mind? What permits them to evaluate and to represent relationships between the distributed results of the various basic cognitive operations that occur in parallel and in relative isolation at lower levels of the brain? What could be the structure of the abstract meta-representations that integrate the modality-specific results provided by the various sensory systems and permit symbolic encoding of both external events and internal states?

One prerequisite for the generation of such higher order descriptions is a mechanism that allows for the binding of distributed first order processes. At the neuronal level the following requirements have to be fulfilled: 1) all computational results, both those of first and higher order processes, must be expressed in a common format to permit flexible recombination. 2) A versatile binding mechanism must be implemented that permits evaluation and representation of the relationships between the results of distributed computations. 3) Expanded storage capacities must be provided in order to maintain temporally dispersed contents in short-term buffers so that they are simultaneously available for the evaluation of relations and for binding. 4) Additional neuronal substrate needs to be provided for the generation of descriptions of higher order. 5) Effector systems are required that are sufficiently differentiated to permit the translation of the results of higher order computations into actions and the communication of the symbolic descriptions to other individuals.

When comparing our brains to those of non-human primates one is struck by their similarity and searches in vain for entirely novel structures that could account for the new, qualitatively different functions. At the macroscopic level, the only noticeable difference between our brains and those of non-human primates is an increase in the surface of the neocortex, and differences vanish nearly completely if one analyses the brains at the microscopic or molecular level. The internal organisation of the various brain structures, including the neocortex, is nearly identical, and the vast majority of the molecules expressed are the same. This leaves one with the conclusion that the new functions that distinguish homo sapiens sapiens from its nearest neighbour species must have been realised simply by the addition of further areas of the neocortex and/or by the rearrangement of connections among neocortical areas.

Comparative anatomy suggests that these additional areas differ from the more ancient areas in the way in which they are connected to sensory systems and effector organs. The new areas in the occipital, parietal and temporal lobes appear to be involved primarily in the refinement of sensory functions while the new areas in the frontal lobes subserve more executive functions such as action planning, short term storage and management of attention. The more recent sensory areas tend to receive their input not directly from the sensory periphery, as is the case for the more ancient sensory areas, but more indirectly via the latter. Moreover, the new areas tend to collect their input not from a single modality as the ancient sensory areas but from different modalities (Krubitzer, 1995, 1998). It is because of this peculiarity that the phylogenetically more recent areas which are topographically intercalated between the monomodal sensory areas have been addressed as association areas. The new areas in the frontal lobes are also more remote from the periphery than the more ancient motor centres. They tend to be connected to effector organs only indirectly via the ancient motor areas and receive most of their cortical input not from the primary sensory areas but from the more recent association areas. Thus, the connectivity of these phylogenetically recent cortical areas is compatible with the view that they re-evaluate and bind the distributed results of primary cognitive operations, and thereby provide the substrate for the generation of higher-order representations.

What remains puzzling, however, is the fact that all these different functions appear to rely always on the same computational algorithm. The intrinsic organisation of the neocortex is extremely complex but surprisingly stereotyped and monotonous. The laminar organisation, the various cell types, and the intrinsic connectivity differ only little between phylogenetically old and more recent cortical areas or between areas devoted to sensory and executive functions. Because the programme for the computational operations performed by neuronal networks is fully and exclusively determined by the architecture and coupling strength of connections, the structural homogeneity of the neocortex implies that the various regions perform more or less the same computations. This fascinating conclusion has recently received strong support from developmental studies in which inputs from the eye have been re-routed by surgical intervention to the auditory cortex, whereupon this piece of cortex developed exactly the same functional features as are normally characteristic for the visual cortex (Sharma *et al.*, 2000).

It appears, then, as if our brains owed their unique cognitive abilities simply to the iteration of processes realised by cortical architectures. All that seemed necessary for the development of new functions was apparently the addition of cortical areas which treat the output of the already existing areas in exactly the same way as these treat their input, which in lower animals comes mainly from the sensory periphery. In conclusion, the new cognitive abilities that distinguish humans from non-human primates seem to have emerged because evolution provided additional cortical areas which permitted reprocessing and binding of the results of first order processes and the generation of higher order, transmodal representations. Interestingly, the evolution of new cortical areas may not have required major changes in the genome as adding one more step of cell division to the division cycles of precursor cells of neocortical neurons can have dramatic effects on cortical cell numbers and hence cortical volume (Rakiç, 1998).

The notion that neocortical modules process signals according to similar algorithms has the additional attractive implication that the results of their computations are likely to be encoded in the same format. Hence, they can be re-subjected in ever changing constellations to iterative processes of the same kind, thus generating representations of an increasingly higher order. Although this view is far from providing a mechanistic explanation for the emergence of phenomena such as phenomenal awareness, i.e. the ability to be aware of one's own sensations and actions, it provides at least an intuition of how brains can apply their cognitive abilities to some of their own processes, thereby creating descriptions of themselves and hypotheses about others.

In conclusion, it appears that any attempt to account for the emergence of those cognitive abilities that we consider instrumental for the evolution of culture needs to be based on an understanding of neocortical functions, and in particular of those that permit the binding of the results of distributed, primary cognitive operations into coherent, modality-independent and symbolic descriptions. Of primordial interest is, therefore, how contents are represented in cortical networks and how dynamic binding of these contents into meta-representations can be achieved.

The Structure of Representations

The hypothesis proposed here is that evolved brains use two complementary strategies in order to represent contents (see also Singer, 1995, 1999). The first strategy relies on individual neurons that are tuned to respond selectively to particular constellations of input activity thereby establishing explicit representations of particular constellations of features. It is commonly held that the specificity of these neurons is brought about by selective convergence of input connections in hierarchically structured feed-forward architectures. This representational strategy allows for rapid processing and is ideally suited for the representation of frequently occurring stereotyped combinations of features. However, this strategy has several limitations. It is expensive in terms of the number of required neurons because it demands at least one neuron per object. Thus, it is not well suited to cope with the virtually infinite diversity of possible feature constellations encountered in real world objects. Moreover, this representational mode lacks systematicity which makes it difficult to encode relations between parts of the same object or semantic relations between different perceptual objects. A detailed discussion of the advantages and disadvantages of representing contents by individual smart neurons is to be found in Singer (1999), von der Malsburg (1999) and Gray (1999). The second strategy, according to this idea, consists of the temporary association of neurons into a functionally coherent assembly which as a whole represents a particular content whereby each of the participating neurons is tuned to one of the elementary features of the respective perceptual object. This representational strategy is more economical with respect to neuron numbers because a particular neuron can, at different times, participate in different assemblies just as a particular feature can be shared by many different perceptual objects. Moreover, this representational strategy allows for the rapid de novo representation of feature constellations that have never been experienced before. There are virtually no limits to the dynamic association of neurons in ever changing constellations, provided that the participating neurons are directly or indirectly connected. Thus, for the representation of highly complex and permanently changing contents this second strategy appears to be better suited than the first.

The meta-representations that result from iteration of cognitive operations are necessarily much richer in combinatorial complexity than the contents of first order processes. In addition, they must be highly dynamic because they need to be re-configured at the same pace as the contents of phenomenal awareness change. It appears then as if the second representational strategy that is based on the dynamic binding of neurons into functionally coherent assemblies would be more suitable for the implementation of higher order representations than the first strategy which relies on individual smart neurons. While the latter can readily be implemented in simple feed-forward networks and hence can be found also in the brains of invertebrates, assembly coding requires neuronal architectures that permit in addition dynamic grouping of distributed responses through re-entry and self-organisation. This necessitates co-operative interactions among neurons and hence a complex network of reciprocal connections. It appears as if such architectures existed only in cortical structures, which may be one reason for the evolutionary success of the cerebral cortex.

Culture as a Prerequisite for the Emergence of Consciousness

The term ‘consciousness’ has a number of different connotations ranging from awareness of one’s perceptions and sensations to self-awareness, the perception of oneself as an agent endowed with intentionality and free will. The first connotation of consciousness, phenomenal awareness, should in principle be tractable within neurobiological description systems because the problem can probably be reduced to the question of how neuronal representations are organised.

Brains that have the ability to bind the results of their distributed computational operations and to thereby generate metarepresentations of their own internal states can realise what one might call, an ‘inner eye’ function. They can become ‘aware’ of their own performance. The emergence of phenomenal awareness, which we readily grant also to higher mammals and primates, can thus be seen as a direct consequence of an evolutionary process; of a process that led to brain architectures which support the generation of metarepresentations by the iteration of elementary cognitive operations. The adaptive value of acquiring phenomenal awareness is obvious. It permits integration of the results of polymodal sensory processes with information stored in the memory and with the status of a value assigning system. Decisions for future acts can thus be based on a rich set of variables, they can be made dependent on what appears to the observer as ‘reasoning’ or ‘internal deliberations’. Thus, brains endowed with such an ‘inner eye’ function can respond with more flexibility to changing conditions than brains that lack phenomenal awareness and are confined to reacting to stimuli without the option of further reflection and internal deliberation. This advantage may have been one reason for the evolution of brains capable of being aware of their own performance.

However, the other aspect of consciousness, the perception of one’s self as an autonomous mental agent endowed with intentionality and free will seems to require explanations which transcend purely neurobiological reductionism. These aspects appear to have another ontological status as the qualia of phenomenal awareness. We perceive ourselves as agents that are endowed with the freedom to decide, implying that the self is actually capable of controlling, by will, processes in the brain. We experience free will as an immaterial mental force that is capable of influencing the neuronal processes required for the execution of actions and, therefore, we perceive it as not derivable from the material processes in the brain. Hence, realities that we experience from our subjective first person perspective seem to differ ontologically from realities that we observe from the third person perspective when we analyse the functions of the brain. This coexistence of different description systems gives rise to several explanatory gaps. If one takes a dualistic stance one has to explain how an immaterial mental entity can interact with neuronal processes and induce action? If one adopts a monistic position, one has to explain how the nervous system, which is a deterministic material system that results from a continuous evolutionary and an equally continuous ontogenetic process can give rise to realities that are experienced as non-deterministic and immaterial. I propose that these explanatory gaps can be closed if one adopts a monistic position but includes as variables not only biological evolution and the physiology of individual brains but also cultural evolution.

I suggest that the experience that makes us believe that we are free is the result of cultural evolution, i.e. of interactions among brains that are sufficiently differentiated to be able to generate a theory of mind. Brains which possess phenomenal awareness and in addition have the ability to signal to one another and to comprehend that they are endowed with this capacity can mirror one another and attribute to themselves what they observe in the respective other. Many of the variables which determine the decisions and actions of the brain are not observable because they are not accessible to phenomenal awareness, and because they are not consciously perceived the most parsimoneous interpretation of the driving force behind the unexplained causes for the actions of the respective other is the assignment of intentionality. Since we are ourselves also unaware of many of the variables which determine our own actions and since others attribute to us intentionality as well, and since this reflexive assignment accompanies us from early childhood throughout life, it appears quite plausible that we adopt this construct as a constitutive element of our self. The experience of an autonomous agent endowed with intentionality would thus be the result of reciprocal cognitive interactions among human beings. The experience of being free to act and as a consequence the conviction that one is responsible would then have to be considered as a product of social interactions and the contents of this experience would have the ontological status of social realities, of cultural constructs.

The mechanisms that enable us to experience ourselves as endowed with mental capacities do, of course, reside in individual brains, but the contents of this experience are derived from social interactions. But why then should the experience of the intentional self be so obviously different from other experiences with social realities such as value systems, that we also derive from social interactions? One explanation could be that the interpersonal dialogue that nourishes the experience of the intentional self is already initiated during a very early developmental stage; a stage that preceeds the maturation of episodic memory. If so, there would be no conscious record, no contextual embedding of the processes that led to the experience of the intentional self. Because of this amnesia these early experiences would lack causation, they would appear as timeless and detached from any real world context. In consequence, the contents of the experience of one's self, although acquired by learning, would be perceived as having transcendental qualities which resist reductionistic explanations.

LITERATURE

Gray, C.M. 1999: 'The Temporal Correlation Hypothesis of Visual Feature Integration: Still Alive and Well', *Neuron* 24: 31-47.

Krubitzer, L. 1995: 'The Organisation of Neocortex in Mammals: Are Species Differences Really so Different?', *Trends in Neurosciences* 18: 408-417.

Krubitzer, L. 1998: 'Constructing the Neocortex: Influences on the Pattern of Organization in Mammals', in M.S. Gazzaniga and J.S. Altman (eds.), *Brain and Mind: Evolutionary Perspectives* (Strasbourg: HFSP Workshop V.), pp. 18-34.

Rakiç, P. 1998: 'Cortical Development and Evolution', in M.S. Gazzaniga and J.S. Altman (eds.), *Brain and Mind: Evolutionary Perspectives* (Strasbourg: HFSP Workshop V.), pp. 34-42.

Sharma, J., Angelucci, A. and Sur, M. 2000: 'Induction of Visual Orientation Modules in Auditory Cortex', *Nature* 404: 841-847.

Singer, W. 1990: 'The Formation of Cooperative Cell Assemblies in the Visual Cortex', *Journal Experimental Biology* 155: 177-197.

Singer, W. 1995: 'Development and Plasticity of Cortical Processing Architectures', *Science* 270: 758-764.

Singer, W. 1999: 'Neuronal Synchrony: A Versatile Code for the Definition of Relations?', *Neuron* 24: 49-65.

Von der Malsburg, C. 1999: 'The What and Why of Binding: the Modeler's Perspective', *Neuron* 24: 95-104.

EARTH SCIENCES: REMARKABLE SCIENTIFIC PROGRESS, EXTRAORDINARY OPPORTUNITY FOR HUMAN BETTERMENT[1]

FRANK PRESS[2]

Humankind enjoys the benefits of living in a unique place. No other known planet has the same balance of conditions necessary to sustain life as we know it. However, in this paper I want to discuss some of our planet's hazards – namely, earthquakes, volcanoes, storms, floods, and the like.

Although I will discuss mostly rapid onset natural hazard events, one must add in these times the perils of El Niño, global warming, industrial accidents, environmental degradation and other consequences of humankind's interaction with the natural environment. Science progresses by challenging conventional wisdom and teaching the world to think in a fundamentally new way. And that is what we need to do about natural hazards.

You will note that I refer to these events as natural hazards, not as natural disasters. The distinction is deliberate. We cannot stop volcanoes from erupting or the earth from shaking. On occasion, winds will blow outside this hall and level the beautiful trees of Rome.

Our planet is affected by an external engine energized by solar radiation and an internal engine driven by Earth's internal heat. They are beyond our direct control. The external engine drives our weather and climate. It has made life possible on Earth but it also is responsible for storms and floods. The internal engine produced the continents, the atmosphere, and the oceans. But it also produces the Mount Pinatubo volcanic eruption and earthquakes in Turkey. As one philosopher said, "Man lives by geological

---

[1] This paper is an updated version of reports I have given elsewhere on several occasions. It includes new scientific results and recent changes in policy.

[2] President Emeritus, U.S. National Academy of Sciences

consent subject to change without notice.” In scientific parlance, “geophysical extremes are inevitable.”

Natural hazards are rare, low-probability events that are natural and unstoppable. Natural disasters are the unfortunately common consequences of these extreme events when they collide with people. As one observer remarked, “we can’t control mother nature but we can affect human nature.” What he meant was disasters can be mitigated because how humans choose to live with the natural environment can be changed by a combination of new scientific knowledge and improved public policies.

Millions of people now die unnecessarily. I believe that reducing disasters – which is to say, the toll of natural hazards – is one of the great challenges of our times. We have the scientific knowledge and practical know-how to partially overcome phenomena that have devastated mankind since before Biblical times. And through science we can learn to do more. It is an opportunity of historic significance. And it is what I will discuss with you today

First, I will outline the extent of the problem and discuss the new scientific and engineering possibilities that allow for improved societal response. Then I will discuss international efforts initiated by scientists and engineers that have begun to show results. The views of public officials in many countries, rich and poor, are changing from fatalism to a proactive and informed pursuit of policies to limit the destructiveness of natural hazards.

The Grim Statistics of Recent Natural Disasters

So let us begin by reminding ourselves just how common and severe natural disasters are. According to the International Decade of Natural Disaster Reduction (IDNDR as it is known), an organization of the United Nations, in the past twenty to thirty years, natural disasters killed more than 3 million people worldwide. More than a billion people have been adversely affected. They have suffered homelessness, injury and disease, catastrophic economic losses, and other personal tragedies. The Munich Reinsurance Company predicted that global economic losses were likely to double in the period 1995-2000. According to the International Red Cross the global losses related to disasters currently amount to some $440 billion each year. In the United States the losses from natural disasters now average about $1 billion per week, with an accelerating trend.

Nearly every nation of the world is at risk from rapid-onset natural hazards. Every year our planet experiences about 100,000 thunderstorms, 10,000 floods, and thousands of earthquakes, wildfires, landslides, avalanches, and tornadoes. There are hundreds of volcanic eruptions and tropical cyclones. Most of these events result in human losses that escape being counted in the casualty and economic loss statistics that were cited earlier.

What I would like to emphasize today is that most of the human tragedy of death and destruction from natural disasters occurs mainly in the developing world. Two-thirds of the world's population lives in developing nations, and these countries bear 95 percent of all disaster casualties. A single major disaster can result in hundreds of thousands of deaths and can set back economic progress in a developing country by as much as five years. The statistics numb the mind. The loss of life per million of population is twelve fold greater in the developing world than in the United States. The economic loss in my country of about a billion dollars a week may seem high, and it is, but annually it amounts to only about 0.7% of the gross domestic product. In poor countries it has been as much as 50% of the G.D.P. In these cases economic development is slowed if not turned negative as scarce resources are diverted to emergency and recovery efforts.

It is easy to see why the impact of these hazards is growing worse by the year despite our increased understanding of them. This is true for several reasons.

– First, the world's population is continuing to grow, and many people are settling in areas of high risk, such as flood plains, coasts, seismic zones, or mountain slopes susceptible to landslides.

– There are 20 megacities in the world with populations exceeding 10 million people. This density of urban population continues to grow for demographic and economic reasons.

– Still another reason that natural hazards are claiming a continually rising number of victims is that so many of the world's buildings and other structures, both new and old, remain unsafe. When a natural disaster hits these areas, not only are more people hurt immediately, but critical life support systems are interrupted, leading to further health problems.

– All this expansion also has altered the natural environment. Deforestation in the Amazon, for instance, has caused an increase in flooding, landslides, and soil erosion. Overgrazing of arid grasslands has accelerated the process of desertification and drought in sub-Saharan Africa.

– Failure to use the existing knowledge developed by scientists and engineers to reduce the vulnerability of structures to earthquakes, storms, floods and other hazards must be reckoned as a factor in these pessimistic statistics.

– And the increasing globalization and interconnectiveness of the world's economy makes it clear that no nation is immune from an immense disaster that can strike anywhere in the world. Disasters can trigger disinvestment and the flight of capital, inflation, indebtedness, bankruptcy. For example, if the great earthquake that struck Tokyo in 1923 were to repeat (as it eventually will) the damage could exceed $1 trillion. According to the Bank of Tokyo such losses could propagate beyond Japan and upset the global economy. For example, Japan could be forced to recall its foreign investments and reassess its role in international financial institutions. This could well precipitate a world recession.

In my own country, millions of people living near the New Madrid fault in our Midwest risk a similar fate due to construction codes that have ignored the possible repeat of a great earthquake that occurred early in the eighteenth century.

The Role of Science in Reducing the Destructiveness of Natural Hazards

The tradition of humankind studying terrifying natural phenomena dates back to ancient times, of course. Our ancestors explained these cataclysms through religious myths, astrology, and the like. Then, with the advance of science, came a truer understanding of hazards as natural phenomena.

Today we understand the origins of earthquakes and volcanic eruptions in terms of the modern theory of plate tectonics. Similarly, there is growing knowledge of the general circulation of the atmosphere, its interaction with the oceans and the generation of weather.

My own background is in geophysics, and I am amazed by what has been learned about earthquakes just since I was in graduate school. The same is true of volcanology, meteorology, and other disciplines, although one also finds an increasing – and very healthy – blurring of these specialties. There are now underway new theoretical approaches, new kinds of experiments, and new data, generating new understanding at a remarkable rate.

Here are some examples of technologies that are now available that can contribute to monitoring and warning systems:

– It is now possible to determine in advance of an earthquake the probability that ground accelerations will exceed certain levels in a district so that building designs and regulations are appropriate for the degree of hazard.

– Real time processing of seismic signals can provide an alert within three minutes via commercial paging systems to police, fireman, utilities, trains, medical and public health authorities. Using GIS the degree of damage in different sectors can be assessed and within hours or less post-disaster rescue and relief agents can reach the neediest districts.

– Real time response can also occur in another way. With computerized digital arrays of seismographs, an earthquake can be located and its time and size determined in about a minute. This information can be signaled instantaneously, well before the slower traveling seismic waves arrive. In some locations such as Mexico City, several hundred kilometers from the earthquake belt it is vulnerable to, a warning can be issued some 70 seconds before the arrival of the most destructive seismic waves – possibly time enough to shut down gas transmission lines and power plants, get fire engines out of their buildings, get school children into protected areas, stop trains and other appropriate actions.

– Many types of volcanic eruptions are predictable from space and from ground observations with sufficient certainty to evacuate affected populations.

– Satellites can monitor severe storms and computers can predict their paths with increasing accuracy.

– Ocean storm surges can be predicted days in advance – very important to places like the Bay of Bengal and the Adriatic Sea.

– The development of advanced Doppler radar technology has greatly advanced our ability to predict tornadoes and other weather-related hazards.

– Computer modeling of watersheds has led to more accurate flood alerts.

– Warning systems for tsunami and landslides are now available for many locations.

Current forefront research is opening the way to new technologies with great potential to reduce even more dramatically losses from natural disasters. Here are some examples:

– Most earthquakes and volcanoes occur at boundaries where tectonic plates collide, separate, or slide past one another. Plans are being made to place instruments at all of the boundaries of a plate that would measure microseismicity, strain accumulation, thermal activity, chemical changes in fluid emanations, and other potentially premonitory indicators of hazardous events.

– Plans are being made to drill into the San Andreas Fault, the most dangerous fault in the United States, at a depth of some five kilometers. Instruments will be emplaced in this zone which could illuminate the nucleation process of earthquakes.

– Synthetic Aperature Radar interference patterns obtained from satellite observations can reveal strain accumulation and release at earthquake faults and show the swelling of a volcano prior to an eruption.

– New satellites such as TERRA can monitor Earth's vital signs such as land, sea, and air temperatures, clouds, aerosols, water vapor and green house gases, ocean currents, winds, pollution, and ecological changes. These can be used to provide earlier warning of severe storms, volcanic eruptions, predict El Niño events, and signal global climatic change.

Unfortunately, many of the currently available technologies I have described earlier are available only in those countries that have the technical, human, and material resources to use them. Hopefully this will change. Nevertheless, there is an enormous amount that can now be accomplished more generally by using knowledge and technical systems that have been around for several decades. The problem is putting all of this know how into general practice – getting the word out to the villages and cities where people need it most, particularly those in the developing world. It requires education that goes beyond individuals and families. It also needs to include training programs for architects, engineers, insurance agents, city planners, teachers, reporters, *and especially government policy makers*. H.G. Wells stated it very well when he wrote: "Human history becomes more and more a race between education and catastrophe."

The first step is risk assessment which combines information on a physical hazard with information on vulnerability to determine the likely impact of a hazardous event. It provides estimates of deaths and injuries, property damage, and economic losses that are likely to occur. Once this assessment is made, a community can undertake disaster reduction programs appropriate for the risk, and organize warning and evacuation strategies to reduce those impacts.

Let me give you some examples. Consider Hurricane Gilbert. This 1988 storm was the most powerful hurricane ever recorded in the Western Hemisphere. Three hundred sixteen people died. That was a substantial loss of life, but it was far lower than the death tolls from hurricanes of smaller magnitude that have swept through the Caribbean. Those earlier storms claimed lives not in the hundreds, but in the tens of thousands. The main difference with Hurricane Gilbert was that people and governments were well prepared. Weather reports and storm tracks were timely and accurate. The public was educated to heed these warnings and to take appropriate actions. Land use restrictions and building codes were in place to minimize the loss of life and property in the Caribbean island nations and Mexico. Governments had emergency teams standing by to provide assistance. So today people are alive to share their memories of Gilbert rather than being remembered among its victims.

Another example is the 1991 eruption of Mt. Pinatubo in the Phillippines. An international team of scientists developed a risk map of the area. Arrays of instruments were established to monitor the seismic activity, the swelling of the volcano as the magma flowed upward, the geochemistry of its emanations. On the basis of these data an alert was issued to the government which then broadcast a warning and proceeded to evacuated more than 80,000 people. Only 300 people perished from this, one of the great eruptions in human history.

Contrast this with a worst case example – the 1985 eruption of the volcano Nevada del Ruiz in Columbia. Scientist warned authorities about the dangers of this volcano when hot gases would sweep across the snow pack near the summit. They had prepared a preliminary hazard map. Unfortunately, there was no government office available to receive this information, no warning or evacuation systems were in place. The eruption followed the course predicted by the scientists and a meltwater-mud flow engulfed and buried the town of Armero. All of its 23,000 inhabitants perished. As the British philosopher John Locke observed, “Hell is truth seen too late.”

It is a sad commentary on our times that the industrialized nations can employ life and property saving measures much sooner and more effectively than those in the less affluent countries. It is a moral imperative that these measures and their associated technologies be made available more widely.

In 1984 I gave a talk before a world conference of engineers calling on the international scientific and engineering communities to become engaged in reducing the toll of natural disasters. The message resonated across professional communities and was endorsed by organizations representing tens of thousands of scientists and engineers. It was recognized from the beginning that addressing disasters with technology was only the precursor to hazard management, which involves the messy political process of balancing interests and priorities, and of implementing change. So, obviously, another challenge we faced was to work with political decision-makers, to apply our improved scientific understanding and technological capacity, to develop both long-term protective measures and shorter-term warnings.

In particular it was necessary to engage the United Nations because of its ability to communicate with and enlist the leaders of every country, rich and poor, large and small. In this we were successful. In response to the initiatives of scientists and engineers in many countries, acting on their new awareness of the opportunities for disaster mitigation, the United Nations declared the 1990s to be the International Decade for Natural Disaster Reduction. I consider it one of the highlights of my career that I helped launch this international program.

To quote Javier Perez de Cuellar, the Secretary-General of the United Nations in the early years of the decade: “The Decade offers an opportunity for the United Nations to demonstrate its catalytic ability to bring together the diversity of skills, resources, and groups needed to stem the losses from natural disasters...It has the moral authority to call for disaster reduction efforts by all nations, including the developing ones where the toll from such disasters is most tragic in terms of human losses and economic setbacks.”

The “Decade,” as it has come to be called, ended last year. However with pressure from the developing nations there will be continuing involvement of the UN. Looking back at its accomplishments

– The decade helped to mobilize scientists, political leaders, and others to overcome people’s fatalism about natural hazards.

– Disaster preparedness offices were organized and hazard assessments were prepared in many countries for the first time.

– Training programs increased the number of disaster professionals by the hundreds.

– Warning systems and evacuation plans were established widely.

– Country development plans were scrutinized for their vulnerability to disasters.

– Disaster mitigation and sustainable development plans have begun to be coordinated.

Although much more could have been done, fewer people will suffer in the years ahead. And as research continues and the new knowledge gained is put to use, large reductions in human and material losses become possible.

I feel strongly that acting to prevent natural disasters is the mark of a civilized society and a primary role of modern government. As a scientist I take great pride that this progress has its roots in science and technology.

So my message in this paper is clear. The human race is more vulnerable than ever to natural hazards. But it also has growing power to predict and provide early warning of many of these hazards and reduce the devastation of all of them. Taking into account the enormous costs of post-disaster relief, pre-disaster mitigation is viewed by many experts as cost effective. A judicious blend of science and technology with enlightened public policy and education could change the course of history.

GLOBAL CHANGE AND THE ANTARCTIC OZONE HOLE

MARIO J. MOLINA

It was only in the second half of the twentieth century that it became clear that human activities may have impacts on the environment truly on a planetary scale. Human beings started altering the surface of the planet a long time ago, at least since they began to develop an agriculture that required plowing, irrigation and the clearing of forests. However, until recently those changes were mostly local, and possibly regional.

The potential impact of human activities on the atmosphere can be appreciated by considering its size: about 95% of its mass resides in the first 20 km above the Earth's surface, whereas the distance between the two poles is 20,000 km. The atmosphere makes life on Earth possible, and yet from a cosmic perspective it is a very thin, very fragile layer. For this reason its chemical composition can be inadvertently changed as a consequence of human activities.

The clearest example of a global environmental problem is the one involving the depletion of the ozone layer of the stratosphere by industrial chlorofluorocarbons (CFCs). These compounds were developed in the 1930's as replacements of the refrigerant fluids that were in use at that time, namely ammonia and sulfur dioxide. These two compounds are rather toxic, and a number of accidents took place when they were accidentally released in small rooms where people were sleeping. The CFCs have two important properties: they are non-toxic and non-flammable, and they can be readily converted under mild pressures from a liquid to a vapor and vice versa, which is what makes them so valuable as refrigerants. The CFCs became very successful in other applications as well, such as propellants for aerosol spray cans. For this reason their industrial production increased rapidly during the 1960's and 70's.

The CFCs are so stable that practically the entire industrial production ends up in the atmosphere. In the early 1970's it became possible to monitor their presence throughout the globe, their atmospheric concentration at that time being at the parts per trillion level. In 1973, together with my colleague Sherwood Rowland, we set out to investigate the fate of the CFCs in the environment; we also wanted to find out if the presence of these industrial compounds in our atmosphere had any significant consequences. We were not aware at that time that another group of scientists had asked the same question, concluding that there was no cause for concern: they reasoned that the CFCs are not only extremely stable, but their concentration appeared so small that no significant effects appeared plausible.

In 1974 we published a very different conclusion, namely that the release of CFCs could lead to a serious environmental problem. To understand how we arrived at such a conclusion, let us examine some important properties of our atmosphere. In the lowest layer, called the troposphere, temperature decreases with altitude; in the next layer, the stratosphere, temperature increases with altitude, giving rise to an “inverted” temperature profile that leads to stability: mixing in the vertical direction is very slow (Figure 1). The troposphere has very efficient cleansing mechanisms: first of all, it has clouds and rain, which remove particles and pollutants that are soluble in water on a time scale of at most a few weeks. Some compounds such as hydrocarbons that are emitted naturally as well as by human activities are not directly removed by rain; instead, they are first oxidized and subsequently transformed into water-soluble species. The stratosphere, however, has no rain, because most water condenses before reaching that layer. Thus, if pollutants are somehow introduced into the stratosphere, they may remain there for periods of several years before being removed by finding their way into the troposphere.

The atmosphere is heated mostly from below, at the Earth’s surface, which explains why it is that temperature decreases with altitude. The reason that temperature increases with altitude in the stratosphere is that there is a component of the atmosphere at higher altitudes that absorbs solar radiation: this is ozone, a form of oxygen with three atoms per molecule. Ozone is extremely efficient in absorbing ultraviolet radiation at wavelengths shorter than about 290 nm, radiation that is damaging to biological systems. In fact, life as we know it could only evolve after the ozone layer was formed. Ozone is a rather unstable chemical species: it is continuously being formed by the action of short wavelength solar radiation (around 200 nm) on molecular oxygen, and it is continuously being destroyed by various chemical processes. Its maximum concentration reaches only several parts per million. In the natural stratosphere the

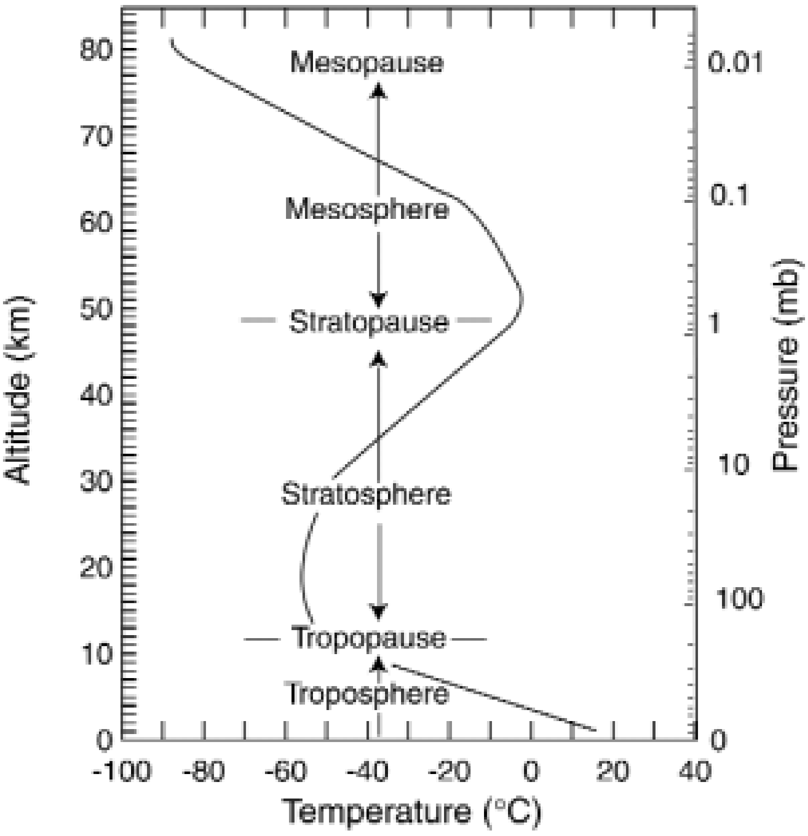


Figure 1. Typical atmospheric temperature and pressure as a function of altitude.

ozone abundance is controlled mainly by nitrogen oxides. These compounds function as catalysts: they are present at only parts per billion levels, and yet they destroy much larger amounts of ozone through a recycling mechanism.

With these ideas in mind we can explain how is it that the CFCs can affect the ozone layer (Figure 2). After their release at the Earth's surface, the CFCs mix rapidly in the troposphere, unaffected by the cleansing mechanisms that operate in this layer. Eventually these compounds reach the stratosphere, and are transported above the ozone layer, where they are

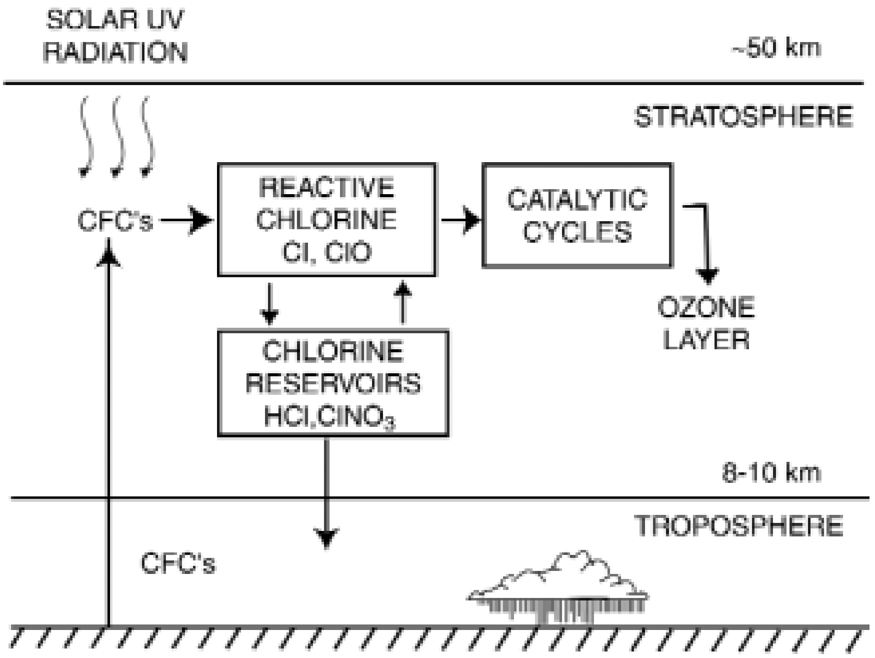


Figure 2. Schematic representation of the CFC-ozone loss hypothesis.

destroyed by short wavelength radiation. The decomposition products from the CFCs are chemically very active, and through catalytic cycles accelerate the destruction of ozone. These cycles provide a very efficient amplification factor: a single chlorine atom may destroy tens of thousands of ozone molecules before returning to the troposphere.

In the years subsequent to the publication of our CFC-ozone depletion hypothesis many experiments were carried out to test various aspects of the hypothesis. Laboratory investigations were conducted to determine the rates of the chemical reactions thought to be important for ozone depletion. Field measurements indicated that the CFCs were indeed reaching the stratosphere, and that their decomposition products were present at the expected concentrations. It took, however, more than a decade to establish that the amount of stratospheric ozone was being affected. The reason is that ozone concentrations have large natural fluctuations, so that a decreasing trend has to be rather large before it can be attributed to human activities.

In 1985 it became apparent that something unusual was happening to the ozone layer over Antarctica: in the spring months – September and October in the Southern Hemisphere – ozone was reaching extremely low values. Nobody had predicted that ozone would first begin to disappear over Antarctica; in fact, a number of scientists first thought that such a disappearance had nothing to do with the CFCs, postulating that natural meteorological cycles were responsible for the ozone changes. Several important expeditions were then organized to probe the stratosphere over Antarctica, using ground observations as well as measurements from aircraft flying through the cold polar stratosphere. The results showed that meteorology alone could not explain the observations. Instead, it became very clear that the drastic depletion of polar ozone was caused by chlorine coming from the decomposition of CFCs at lower latitudes. The depletion became known as the "Antarctic ozone hole".

It soon became clear that the reason ozone depletion was taking place specifically over Antarctica was related to the presence of thin ice clouds. As mentioned above, the stratosphere is very dry, and hence mostly cloudless. However, the temperature drops so much over Antarctica – down to –80 °C – that even the parts per million of water vapor that are present there condense to form ice crystals, making polar stratospheric clouds (PSCs). We were able to show with laboratory experiments that those ice crystals "activate" chlorine by transforming relatively stable species such as hydrogen chloride (HCl) and chlorine nitrate ($ClONO_2$) to molecular chlorine (Cl_2). This last compound is a green gas, and hence it decomposes readily by absorbing even the faint amount of light that from the sun that reaches the Antarctic stratosphere in the spring, after the long polar night. Molecular chlorine decomposes to yield free chlorine atoms, which then destroy ozone very efficiently through catalytic cycles. This destruction process is particularly efficient in the presence of PSCs because the cloud particles scavenge nitrogen oxides, which normally interfere with the chlorine catalytic cycles.

Several expeditions were launched in the years following the initial discovery of the ozone hole to measure trace species in the stratosphere over Antarctica. The ground-based National Ozone Expedition (NOZE) to McMurdo, Antarctica, provided the first evidence for the crucial role played by industrial chlorine in the depletion of ozone in 1986 and 1987. A subsequent expedition based on aircraft flights over Antarctica from a base in

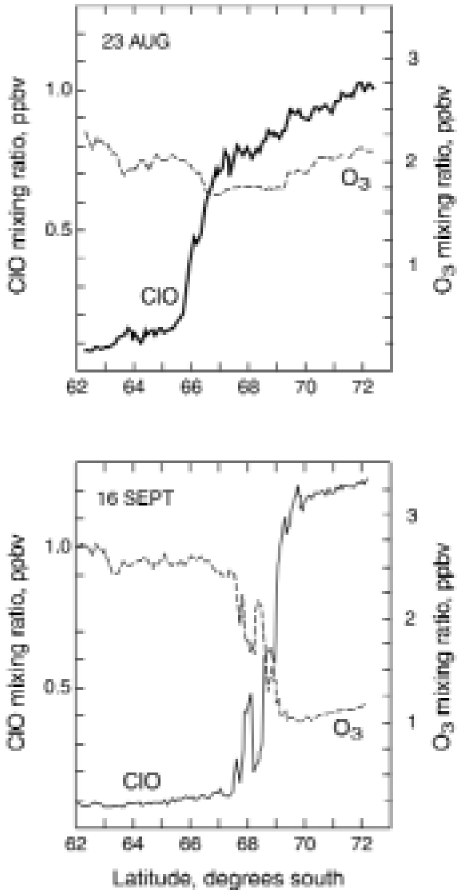


Figure 3. Aircraft measurements of chlorine monoxide by James Anderson and coworkers, and of ozone by Michael Proffitt and coworkers, conducted on August 23 and September 16, 1987.

southern Chile provided some of the most convincing pieces of evidence in 1987. At the time that ozone is strongly depleted in the Polar stratosphere (during the spring), a large fraction of the chlorine is present as a free radical: parts per billion levels of chlorine monoxide is strongly anti-correlated with ozone loss (Figure 3). These results were further confirmed by satellite measurements.

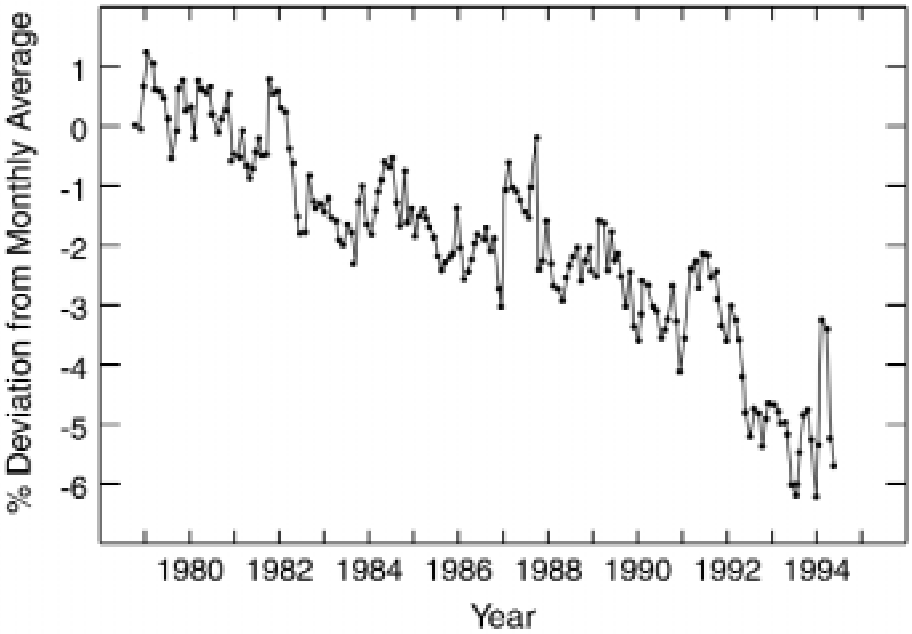


Figure 4. Trend in global ozone values averaged between 60∞North and 60∞South.

The Antarctic ozone hole is a very striking phenomenon: in recent years measurements show that more than 99% of the ozone disappears every spring over a 5 km altitude range in the middle stratosphere, where it is normally most abundant. Ozone produced at low latitudes replenishes the polar stratosphere in subsequent months, so that its level returns to near-normal values in the summer. Significant depletion also takes place over the Arctic, but it is less localized and less severe, because the northern polar stratosphere does not get as cold. In fact, over the past decade there has been a measurable downtrend in ozone levels even at mid-latitudes: the concentrations averaged over latitudes between 60° North and 60° South were about 6% lower in 1994 than in 1980 (Figure 4).

How has society responded to the stratospheric ozone depletion issue? In 1978 the use of CFCs as propellants for spray cans was banned in the United States, in Canada, and in the Scandinavian countries. In 1987 many nations negotiated an international agreement, coordinated by the United Nations

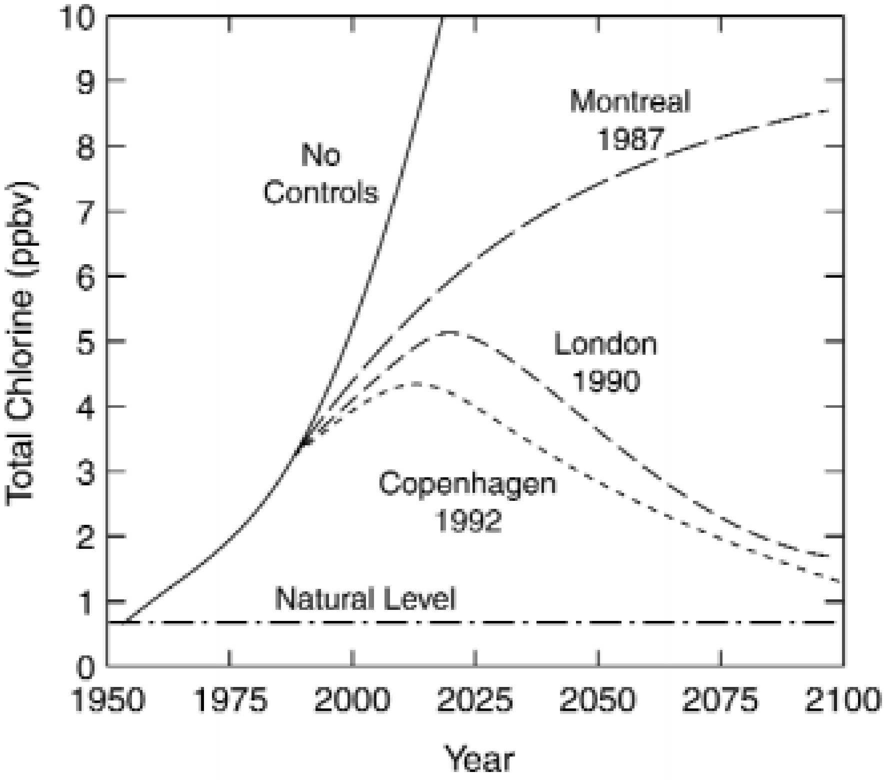


Figure 5. Measured and projected organic chlorine concentrations in the atmosphere according to the provisions of the Montreal Protocol and subsequent amendments.

Environment Program, calling for restrictions in the manufacture of CFCs. The agreement – called the "Montreal Protocol on Substances that Deplete the Ozone Layer"– has provisions for periodic revisions in response to scientific and technological developments. The strong scientific evidence linking ozone depletion to the release of CFCs lead to important changes in the Protocol. It was first strengthened in London, in 1990, and later in Copenhagen, in 1992, where the various nations participating in the negotiations agreed to a complete phase out in the production of CFCs by the end of 1995. This phase out is restricted to the developed countries; developing countries have a grace period to facilitate a smooth transition to CFC-free technologies.

Measurements have shown very clearly that chlorine levels in the stratosphere have been increasing rapidly since the 1970's, as a consequence of the increase in the concentrations of CFCs. There is one compound of natural origin, methyl chloride (CH_3Cl), which provides a background source of chlorine to the stratosphere and whose concentration has not changed with time. At present, however, the amount of chlorine reaching the stratosphere from the industrial CFCs is several times larger than the amount of natural origin. Thanks to the Montreal Protocol the atmospheric concentrations of the CFCs are no longer increasing. Nevertheless, because of their long residence times in the environment – of the order of a century – the chlorine concentration in the stratosphere is expected to decrease only very slowly (Figure 5), so that the Antarctic ozone hole will not disappear for several decades.

The formulation of the Montreal Protocol sets a very important precedent for addressing global environmental problems. The Protocol demonstrates how the different sectors of society – industrialists, scientists, environmentalists and policy makers – can be very productive by working together, rather than functioning in an adversary mode. Another important precedent of the Montreal Protocol was the establishment of a funding mechanism – financed by the industrialized countries – to help the developing countries meet the costs of complying with the Protocol.

The development of new technologies also played an important role in the solution to the problem. A significant fraction of the former CFC usage is being dealt with by conservation and recycling. Furthermore, roughly a fourth of the former use of CFCs is being temporarily replaced by hydrochlorofluorocarbons (HCFCs) – these are compounds that have similar physical properties to the CFCs, but their molecules contain hydrogen atoms and hence are less stable in the atmosphere. A large fraction of the HCFCs released industrially is oxidized in the lower atmosphere before reaching the stratosphere. Some hydrofluorocarbons (HFCs) – which do not contain chlorine atoms – are also being used as CFC replacements, e.g., HFC-134a (CF_3-CH_2F), for automobile air conditioning. About half of the CFC usage is being replaced by employing new, different technologies. For example, CFC-113 – used extensively in the past as a solvent to clean electronic components – is being phased out by using other cleaning methods such as soap-and-water or terpene-based solvents. But the most elegant new technology involves the manufacture of electronic boards that no longer need to be cleaned.

The CFC-ozone issue has shown us that human activities can lead to serious environmental problems not just on a local, but also on a global scale. Society faces many other environmental challenges in this coming century. For example, pollution in many large cities is already a very serious local problem; when coupled to pollution resulting from the burning of forests, the problem is beginning to reach global proportions. One of the key elements needed in addressing global environmental issues is to realize that practically all the large problems that society is facing are interconnected. International cooperation will be essential to the solution of these problems.

SCIENCE FOR MAN AND MAN FOR SCIENCE: THE VIEW FROM THE THIRD WORLD

MARCOS MOSHINSKY

INTRODUCTION

My contribution to this meeting of the Pontifical Academy of Sciences has suffered many fluctuations. I initially received information that the general title of the Symposium was going to be the one given in the first line of this paper, which indeed suggested to me the title that I should use. I then received information that the general title had been changed to "Science and the Future of Mankind" and I was requested to make a contribution more in line with of my own specialization, which is physics. I then sent a one page abstract on "Twentieth-Century Physics and Beyond", of which I have distributed a copy.

When I made a presentation in Mexico of a first draft of this new contribution I realized that in twenty minutes I would barely be able to deal with the electron, and so I decided to go back to my original title, which caused much confusion in the Secretariat of our Academy as, initially, two proposals were distributed.

Returning to my original title I want to modify it a little. It speaks of the 'Third World' because, originally, the First included democratic nations with market economies; the Second referred to socialist countries which had chosen a different path of development; and the Third World included everybody else.

Today the socialist countries have essentially disappeared and even China, while still totalitarian, is now following a market economy. Thus I would like to make the following classification: developed countries, developing countries, and underdeveloped countries, which are likely to stay that way. I will not list by name the classification of countries, except for my own Mexico, as I do not wish to offend anyone, but the actual title of my talk will be “Science for Man and Man for Science: The View from Developing Countries”.

Due to the limitations of time and space, I will confine my presentation to a few examples, first indicating the way that science has affected men in the countries mentioned, and then speaking of men in them who have contributed to this aspect of science.

1. THE POPULATION EXPLOSION

This subject is a sensitive one within the Pontifical Academy of Sciences, but I consider that we must tackle it if among our duties there is that of *advising* the Church on scientific matters. I underline the word ‘advising’ because the Academicians do not presume to dictate the course of the Church on any matter, and the Church, we hope, does not wish to dictate its viewpoint to the Academicians. The example of Galileo shows the dangers of not following such a course.

The reason that I mention this subject in my talk is that, in my opinion, nothing has contributed more to the problem of the population explosion than the great advances in medical and biological sciences which started about the middle of the nineteenth century and increased enormously during the twentieth.

There is no question that the eradication of some diseases such as small pox and the understanding of how others, such as cholera or malaria, spread, has helped to reduce the mortality rate in developing countries, while the birth rate has decreased much more slowly. In my own country, Mexico, I have seen this phenomenon during my lifetime as the population increased from 20 million in 1940 to 100 million today. Similar situations hold in most of the other developing countries.

One could argue that due to the size of most of these countries the population expansion has not been such a bad thing. The problem, though, is not so much the expansion, but the rate at which it takes places. The Mexico of the year 2000 has a much larger class of middle and rich people than in 1940, but while maybe proportionally the number of poor has diminished, in absolute numbers it has grown and the increase of facilities for work, education, housing etc., cannot keep up with the increase in population. Of course this situation is not only due to the demographic explosion because there are other causes such as corruption, exploitation, political in-fighting, etc., but nevertheless the application of scientific knowledge to the health of the population of developing countries has contributed, in many of them, to bringing about an average life expectancy which is not very far from that of developed countries, while the birth rate is several times higher.

There is no question that science can also contribute to bringing about a lower birth rate in these countries, but many obstacles are in the way, on which I will not dwell as they are not of a scientific nature.

What about "man for science" in the biomedical sciences in the developing countries? In view of the gravity of the diseases that existed in these countries, in the nineteenth century they had already started to develop scientific groups to attack these health problems. It is sufficient to mention the name of the father of our former President, Carlos Chagas, to see for how long biomedical scientists in developing countries have been active. We can say that at the present time most disease prevention activity in developing countries is being carried out by local people, who probably make up the largest group of the scientific establishment in these countries.

2. GENETICALLY MODIFIED PRODUCTS

Whereas the first half of the twentieth century witnessed its greatest development in the physical sciences, it is likely that history will consider that the second part of the century was marked more by the development of biology in its genetic aspects.

The discovery that the DNA molecule carries genetic information, and the manipulation of this and related molecules to modify the character of many living species, was one of the great triumphs of twentieth-century science, and this is likely to be even more important during the twenty-first century.

My discussion will center on the genetic modification of plants to make them more resistant to pests or to improve their characteristics for human consumption.

Time limits me to this last aspect and, in particular, to the development of rice with beta-carotene to replace normal white rice, which does not have this substance. This problem is important because rice is the main source of food for more than half of the population of the world, most of whom reside in developing countries.

Over the last few years most educated people have been exposed in newspapers, books, television, etc. to the fight going on between those who believe that genetically engineered products are fundamental for a sustainable and developed world and those who argue that these products need to be very thoroughly tested in order to guarantee that their use does not lead to lethal unexpected consequences.

There is some sound argument in both points of view, but what is certain is that scientists will continue to practice genetic engineering in order to more effectively understand the role of the genes of all species and, in particular, those that we are now learning about through the human genome project. Thus, as science cannot be stopped we must direct more and more effort to studying the benefits and dangers of the application of this knowledge.

In developing countries there is great interest in the advances in genetics and biology in general, and while, for economic reasons there is, as far as I know, no direct contribution to the mapping of the human genome, there is no question that in these countries there are many scientists who will be ready to make use of the new knowledge in the field as soon as it becomes available.

The number of geneticists and molecular biologists in developing countries is still small as compared with advanced countries, but they constitute an important part of the scientific establishment of those countries. It is possible that the increase in their numbers will be faster than will be the case with most of the other branches of science in the countries mentioned. This is because their eventual influence on the life of their populations is likely to be greater.

3. NUCLEAR ENERGY

This subject has developed during my lifetime because I was a member of the first generation of graduate students who entered Princeton University after the Second World War.

Several of my professors had participated in the Manhattan Project but for the most part they had taken part in developing nuclear reactors for the production of plutonium. However, they were keenly aware that their designs, with technological modifications already available in the market place, could be used to generate energy, mainly in the form of electric power.

Thus fifty years ago people were enthusiastic about the prospect of nuclear energy and considered that science and technology could solve any remaining problem.

How different from the view today! In most countries nuclear energy is a “bete noir” which they must get rid off, without there being a thought about the dangers that all other forms of energy production involve.

There is no question that nuclear energy presents dangers of which people were not fully aware fifty years ago, but in the same way that science and technology made nuclear energy possible, so can we expect that eventually they will be able to deal with these dangers.

How is nuclear energy seen in developing countries? Unfortunately, most of them have not followed the example of France, which started by improving its scientific base after the Second World War and, at the same time, by training nuclear technologists, some of them in foreign countries. As a result, France was able to develop its nuclear energy program with its own personnel who knew all the aspects of the problem including its dangers. As I recall, France now produces from nuclear reactors about 70% of its electricity needs and its safety record is commendable.

Most developing nations have not followed this path, because while physics and related sciences were developed (there were 3 Ph.Ds. in physics in Mexico in 1950, and they are about 1,000 now, which is still a very small number for a population of 100 million) they had little influence on the advance of the nuclear program. Most developing nations bought nuclear reactors and trained the personnel that was going to operate them in developed countries. Thus they do not have a full understanding of the processes that France, for example, has. In any case, nuclear energy contributes only a small part of the electric power that is required in developing countries.

We must remember that while producing energy from coal or oil in the form of fire can be done by almost anybody, nuclear energy is the result of extensive scientific and technological inquiry. Thus, developing nations must increase their human infrastructure in the sciences and technology that underlie nuclear power. In view of the dangers of fossil fuels (earth warming, air and water pollution, etc.) I believe that the nuclear energy option will continue to be considered in the future, either in the form of safer fission reactors or, eventually, through their substitution by fusion reactors.

4. THE ELECTRON

The two most basic contributions of physics during the twentieth century, both to science and modern living, were probably the electrons and quanta, which are symbolized by the letters e and $\hbar$.

Time restrictions allow me only to deal with e in the last section of this paper. While the final discovery of the electron was attributed to Thompson in 1897, there is no question that the full understanding of its impact on all aspects of human life took place in the twentieth century.

In this paper I cannot go into the appearance of the electron in deep problems of physics, going from solid state to elementary particles. I will concentrate, instead, on two practical applications: television and computers.

There is no question that without electrons television screens would remain blank and we would not even be able to generate the electro-magnetic waves that carry information to them.

Science and technology were absolutely essential for the development of the television. It is a shame, though, that this very major invention is mainly used for advertising or the transmission of stupefying programs. This, however, is a problem that affects equally the three types of nations of the world: the developed, the developing and the undeveloped. Discussion about it is not appropriate in a paper dealing only with the view from the developing world.

The computer is another matter. It may be the biggest technological revolution that took place in the twentieth century, and it is now affecting all the people of the world.

In the developing world, the influence of the computer is ambivalent. On the one hand, it appears everywhere in all the parts of the societies of developed countries, ranging from research institutions to restaurants. On the other hand, I can give the example of Mexico, in which a recent statistic mentions that 52% of the population has never made a telephone call. For these people, for whom a phone seems to be a magic invention, the computer lies completely beyond their understanding.

The impact of globalization, felt throughout the world, requires eventually that every single human being should be computer-proficient or, at least, have direct access to individuals with this knowledge. In developing countries, the more advanced part of the young population has made computing science and business administration the two most popular fields of the curriculum in all institutions of higher learning. On the other hand, the more retarded part barely finishes primary school and has a rudimentary knowledge of reading, writing and arithmetic.

The computer has given to man an extraordinary product of the development of science, particularly in its mathematical and physical branches. In the developing countries the men that can make full use of this product, and even contribute to its further development, must become aware of what its effect is on the other half of the society in which they live, If they do not invest part of their time in making the majority of their population computer-literate, they risk creating a cleavage that may create unbalance in their countries.

CONCLUSION

I have tried to show in this paper – through the use of a few examples – what science has done for man in developing countries, both in positive and negative terms. I have also tried to show that the men engaged in science in these countries, who are still very few when compared to those in the developed world, should struggle to increase their numbers and then not only contribute to the international development of science but also fight to ensure that these developments do more benefit than damage to the countries in which they live.

PHYSICS IN THE LAST CENTURY AND IN THE FUTURE

RUDOLF L. MÖSSBAUER

During the last century there were three major developments in physics: 1) the special and general theory of relativity; 2) quantum mechanics; and 3) the Standard Model of elementary particles. This paper will deal with these three developments and also with some new developments, in particular the Big Bang, Einstein's cosmological constant, accelerators, and some of the future realms of physics.

There have been several major developments in astronomy, starting with the Greeks. Physics proper started with Galileo Galilei because only in his time did there begin a systematic check of theoretical considerations through actual observation. During the last century there were three major developments in physics:

1) the development by Einstein of the special theory of relativity, i.e. of a new understanding of space and time and of the fact that the velocity of light is constant in all frames. This development included the famous relation between energy and mass: $E = mc^2$. This new development, which led in particular to the abandonment of the notion of an ether, had already been included in the description of electromagnetism by Maxwell, but it had been done then without comprehension. The last century also saw – again by Einstein – the development of general relativity, i.e. the development of a new geometry leading to a curvature of space and time due to the assembly of mass.

2) The development of quantum mechanics.

3) The development of the Standard Model of elementary particle physics, which in group theoretical notation reads $SU(3)_C \times SU(2)_L \times U(1)_Y$. Here, the indices stand as follows: C for colour, L for left-handed weak interaction, and Y for hypercharge. The first factor represents the strong interaction, while the other two factors represent a near unification of the

electromagnetic and the weak interactions. I say near unification, because the relative strength between both interactions, the so-called Weinberg angle, still had to be inserted by hand. I shall concentrate here for reasons of time on the more recent Standard Model. This model obviously does not contain the gravitational interaction. Gravitation plays at present only a role when bodies of astronomical dimensions are involved. We feel Gravitation only for that reason so strongly because we are attracted by the entire Earth, i.e. a body of astronomical dimensions. Gravitation at distances prevailing now on earth is negligible compared to the other interactions. It is only at much shorter distances, which are now not available, that Gravitation played a role. Such small distances prevailed in the vicinity of the Big Bang, which according to the majority of physicists is at the origin of our Universe. There are several arguments in favour of such a Big Bang: There is the primordial abundance of isotopes, there is the fact that most galaxies are receding from us (the Hubble-shift) and there is the electromagnetic background radiation held to be a leftover from the Big Bang. Until recently we have assumed that the mass content of the Universe, the so-called critical mass, just corresponds to that matter, where the Universe after an infinitely long time is neither receding nor approaching. We would speak in such a case of a Euclidian or flat Universe. It is well known that luminous matter plays only a minor role in the composition of our Universe. Exceeding the luminous part by some 90% is Dark Matter, and nobody knows what it consists of. We know of the existence of this Dark Matter very well from the observations of the Hubble red-shift phenomenon, which yields a much larger mass than is observed in the luminous part alone. There are indications, however, that Gravitation may be inverted at very long distances of our Universe – distances far exceeding our solar system. This leads to a renewed introduction of Einstein's cosmological constant, which is in agreement with the equations of the general theory of relativity. The cosmological constant was introduced by Einstein in order to explain a static Universe, long before the knowledge of an expansion of our Universe. Nowadays we know Hubble's law, which involves an expansion of our Universe, and it is suggested that at its rim this Universe undergoes an acceleration rather than an attraction, as implied by Gravitation. Even the vacuum has a non-vanishing energy according to the present quantum field theory. Why the vacuum energy density is not much greater than is presently observed is at present a mystery. This aspect of the cosmological constant is one of the fundamental mysteries of present fundamental physics. The presence of Einstein's cosmological constant or of an equivalent thereof is still an open question. It will presumably be dealt with in further talks.

We are presently capable of reaching the Big Bang by up to some 10^{-44} sec, but we cannot get closer because we do not known how to quantise Gravitation. At the high temperatures existing in the vicinity of the Big Bang, where Gravitation becomes of the same order as the other interactions, we necessarily must quantise Gravitation, which, however, is something which at the present nobody knows how to perform.

It might well be that all interactions reunite to one interaction if we get close to the Big Bang, at some 10^{19} GeV, leaving just one interaction constant. Let me make a joke here, which goes back to Gamov (who together with Lemaître is the father of the Big Bang): what did God do before he created our world by performing the Big Bang? He created hell in order to put in it those people who ask such questions.

We know that the Standard Model cannot be the final answer because of a large number of parameters which have to be inserted into this model by hand. A complete theory would have to explain all these parameters. People have tried experimentally to go beyond the Standard Model, but so far in vain, with one possible exception: the oscillations of atmospheric neutrinos as observed by the Japanese in the Super-Kamiokande experiment.

It might well be that deviations to the Standard Model appear usually only at much higher energies, close to the Big Bang, and that we are visualising a great desert between energies presently available in accelerators – some 10^2 GeV = 10^{11} eV – and energies close to the Big Bang – some 10^{19} GeV = 10^{28} eV. Such a phenomenon, in my opinion, is suggested by the fact that we presently measure the fourth and fifth decimals of the parameters entering the Standard Theory.

It is not clear whether string theories will provide a conclusive answer to the various questions which are raised. For example: why are we living in three spatial dimensions and one time dimension – altogether four dimensions – and not in other dimensions? String theory favours at the moment just eleven dimensions, with the exceeding dimensions being curled up. Or do dimensions beyond four extend to infinity, without leaving any experimental traces? A possible way out, which is favoured in the so-called superstring theories, would be the introduction of supersymmetric particles. We know that at present particles appear either as Bosons, in which case they carry an integer value of their spin – one way of saying that their intrinsic angular momentum is integer – or they appear as Fermions, in which case they carry a half-integer value of their spin. Theoreticians suspect that the arbitrary separation between Bosons and Fermions does not exist and that in reality we have a supersymmetry, i.e. a unification between both schemes. We do not know whether this is right or wrong, but the lightest supersymmetric particle, being of an order of 100-1000 GeV, should be observable in the near future, if it exists. These superstring theories have the additional advantage of quantising gravitation, but this feature still has to verified, with space and time losing their meaning when approaching the present theoretical limit.

There are in fact close ties between elementary particle physics and astrophysics, because many reactions happening in outer space are of relevance to particle physics as well. As an example, we may cite the dark matter problem, which means that the majority of matter is non-radiative, though well known to be there. It is clear that Dark Matter consists of unknown particles – perhaps super-symmetric particles?

In the present model of elementary particles all matter is made from quarks and leptons and there are four forces. These elementary particles and their interactions are shown in Fig.1. It might be, though this is very unlikely, that the present particles are not elementary, but such a feature would for its verification require accelerators of a higher energy than is presently available. This is because smaller distances, according to the uncertainty principle of quantum mechanics, require higher energies.

In addition, we have no ideas about the sizes of all of our natural constants. Are we living in just one Universe and are there many others, maybe an infinite number of them? Are these other Universes carrying other values of their natural constants? We just don’t know.

I shall refrain here from making predictions about future experiments because most basic experiments are anyhow fortuitous. Yet there are several areas where progress will be made. First of all, there will be developments in biology, where physics will continue to make major contributions. It should be noted that all developments in biology so far have shown that everything can be explained on the basis of physics. Whether or not this also explains the process of living still has to be seen. A second area which promises real strides in the future is developments in astrophysics and cosmology, where we are still at the very beginning of our knowledge. Here we are beginning to do experiments and no longer have to rely on mere observations instead. A third area of great promise is that of synchrotron radiation. A fourth area – though of a more technical nature – is the development of nanostructures, which on the one hand make atoms visible and on the other deal with chemical reactions in the spikes of the used ‘raster micoscopes’. A fifth area of interest will probably be neutrinos, because in contrast to the charged elementary particles we hardly know anything about these elementary particles and this in spite of the fact that they were already introduced into physics some seventy years ago. We suspect that oscillations lead to a mixture of such particles, attributing masses to them in a similar fashion to that done with quarks. Such a suggestion is made in connection with the observed solar neutrino deficit. The Japanese observation on atmospheric neutrinos is another hint on neutrino-observations. It will take many years to prove or disprove these experimental observations.

The existing circular accelerators have reached their limits, with linear accelerators still being projects of the future. This is a consequence of the fact that circular accelerators, because of their intrinsic acceleration, always produce synchrotron radiation, which with increasing energy reaches practical limits. We may mention here the LEP (large electron-positron) accelerator at CERN (Centre Etudes pour Radiation Nucleaire) near Geneva. It presently goes up to an energy of some 200 GeV, has a circumference of 27 km, and will be replaced in the same tunnel by a proton-antiproton accelerator called LHC (large hadron collider), which will start to resume operation in 2005 and presumably will be the last circular machine to be built at these high energies. We hope that we will achieve with this accelerator a measurement of the Higgs particle, which would be indicative for masses. Another big circular accelerator runs at the Fermi-Lab near Chicago, with a centre of mass energy of some 1.8 TeV (terra electron volts = 10^{12} eV). It will be surpassed by the LHC which when operative will carry a centre of mass energy of 14 TeV. I would like to mention in this context that DESY (Deutsches Elektronen-Synchroton = German electron synchrotron) at Hamburg/Germany was planning to built a linear accelerator with an energy of 750 GeV, which, presumably for financial reasons, may not be constructed. Only the stage with the free electron laser, producing synchrotron radiation in the 1 Å region, which requires much less energy and therefore much less money, will, it is supposed, be built.

Radioactive beams are presumably the only remnant in nuclear physics which are of real interest, because it is only with such beams that one can study reactions which do not persist on earth, yet are of relevance for stellar reactions.

You will well realise that we know a great deal in physics but that in principle we know very little about our world. Many of the crucial discoveries will be left for the future.

Figure 1. Present elementary particles and their weak interactions, arranged in three families, using for quarks and leptons the standard notations u, d, c, s, t, b = up, down, charm, strange, top, bottom quark, e, μ, τ, ν_e, ν_μ, ν_τ = electron, muon, tauon, electron neutrino, muon neutrino, tauon neutrino.A family lepton number can be attributed to each of the lepton families. The general interactions between elementary particles are also shown.

Elementary particles in electro-weak interaction (left-handed particles)

$$\begin{pmatrix}u\\d'\end{pmatrix}\begin{pmatrix}c\\s'\end{pmatrix}\begin{pmatrix}t\\b'\end{pmatrix}\quad\begin{pmatrix}\nu'_e\\e^-\end{pmatrix}\begin{pmatrix}\nu'_\mu\\\mu^-\end{pmatrix}\begin{pmatrix}\nu'_\tau\\\tau'\end{pmatrix}\text{ where }\underbrace{\begin{pmatrix}d'\\s'\\b'\end{pmatrix}}_{\text{weak eigenstates}}=\underbrace{U}_{\text{mixing matrix}}\underbrace{\begin{pmatrix}d\\s\\b\end{pmatrix}}_{\text{mass eigenstates}}\text{ and }\begin{pmatrix}\nu'_e\\\nu'_\mu\\\nu'_\tau\end{pmatrix}=\underbrace{V}_{\text{mixing matrix}}\underbrace{\begin{pmatrix}v_e\\\nu_\mu\\\nu_\tau\end{pmatrix}}_{\text{weak eigenstates}}$$

plus antiquarks (right-handed particles) and antileptons (right-handed particles)

Interactions between elementary particles

Example	Strong Interaction	Electromagnetic Interaction	Weak Interaction	Gravitational Interaction	Mediating particles
Proton	•	•	•	•	(3 quarks)
quark	•	•	•	•	gluons
electron		•	•	•	$W^\pm$, Z^0, photons
neutrino			•	•	
				•	graviton

Mixing matrix for three particles: Three mixing parameters and one phase yield altogether four parameters. There exist also two mass parameters $\left|\Delta m_0^1\right| = \left|m_1^2 - m_2^2\right|$

ad 1) The special theory of relativity started with the famous paper by Einstein in 1905, which had far reaching effects about all our physical measurements. In modern language, this paper contained the invariance of the product $\vec{r}'^2 - c^2t'^2 = 0$, irrespective of an observer. This equation of a wavefront holds in any frame and thereby gives rise to the so-called

Lorentz transformations, which transform systems of different velocities into each other. In particular, the equality of time depends on the location, eliminating thereby the need for absolute time and of an 'ether'. The new theory means, in reality, abandoning the Galilean transformations, while Maxwell's equations for electromagnetism already contain the new form. The theory includes the principle of equivalence. The special theory of relativity is confined to motions, which are uniform relative to each other, corresponding to so-called inertial systems. This specific feature was dropped in the general theory of relativity., which had been established in 1915 by Einstein as well. This theory, which is too complicated to be presented here, boils down to the equation $R_{\mu\nu} = - kT_{\mu\nu}$, where $T_{\mu\nu}$ is an energy-momentum tensor describing the distribution of matter, k is a constant and $R_{\mu\nu}$ is a tensor describing a measure of the curvature of space. The curvature of space-time is thus related to the distribution of mass in space.

ad 2) The development of quantum mechanics started in 1900 with the famous paper by Max Planck on black body radiation, which on the one hand was correct, but on the other hand was performed without full comprehension. It was Einstein who introduced in his paper on the photo-electric effect in 1905 the proper relation between energy and frequency, although it was only in 1924 that deBroglie also introduced the relation between momentum and wavelength. Einstein in 1905 and deBroglie in 1924 thus established the laws $E = \hbar\omega$ and $|\vec{p}| = \hbar|\vec{k}| = \hbar/\lambda$, leading to a duality between waves and particles. This dualism was verified for electrons in 1927 by the experiment of Davisson and Germer. A non-relativistic quantum theory is traditionally specified as quantum mechanics, with the number of particles being constant. Radiative changes of particle numbers are in this theory performed in a semi-classical way. By contrast, a relativistic quantum theory is based on the principles of the theory of relativity. Again by contrast, a quantum field theory emphasises the creation and the annihilation, i.e. the changes in the number of elementary particles.

The sole interpretation of quantum mechanics, which is compatible with the Schrödinger function Ψ, is an interpretation of Ψ as probability amplitude. The quantity $|\Psi|^2$ then is the probability density dP/dV.

In a non-relativistic quantum theory, we may represent operators either in the form of differential operators or in the form of matrix operators. By consequence, there are in principle two descriptions of a non-relativistic wave equation, one is Schrödinger's wave mechanics and one is Heisenberg's matrix mechanics. Both descriptions really give the same result. A relativistic quantum theory was later on presented by Gordon and Klein for Bosons (particles with an integral number of intrinsic angular momentum or spin) and by Dirac for Fermions (particles with a half-integer number of spins), leading to the concept of antiparticles.

ad 3) The development of the Standard Model assumed, in particular, the existence of a renormalisation for the electroweak interaction, a theoretical development which led only last year to the Nobel prize for t'Hooft and Veltman. Their work was conducted within the framework of a relativistic quantum field theory. It has been well known since the fifties that QED (quantum electrodynamics) is quite suited to the calculation of electromagnetic interactions at any energy with high precision. This treatment leads to the fact that all infinities produced in the theory by quantum mechanical fluctuations can be eliminated by introducing changed (called renormalised) physical quantities such as charge and mass. The equations of QED necessitate a combination of Dirac's relativistic equation for fermions and of Maxwell's equations for photons. The quantum field theory of the colour force is known as quantum chromodynamics (QCD), which leads, in particular, to the SU(3) model.

Gauge theories are responsible for strong, electromagnetic and weak interactions. In particular, the gauge theory for both weak and strong interactions is non-Abelian, causing interactions between the particles mediating the interactions. In classical physics, gauge transformations mean that the relevant potentials are only defined up to arbitrary gradients, i.e. for a vector potential $\vec{A} \rightarrow \vec{A} + \vec{\nabla}\chi$ and for an ordinary potential $V \rightarrow V + \partial\chi/\partial t$. In quantum physics, gauge transformations mean in addition the replacement of Ψ by an arbitrary phase factor $\Psi \rightarrow \exp\{i\alpha)\Psi$,? where α is constant (global phase invariance). A local phase invariance $[\alpha \rightarrow \alpha(\vec{x}, t)]$ leaves the phase of the wave function open, though leaving the probability unchanged. Perhaps all the various gauge theories can be understood on the basis of a single gauge theory. A truly unified theory of all four interactions (called the 'theory of everything', TOE) would involve only one gauge coupling constant. Such a theory would also have to abandon the customary distinction between quarks and leptons, which holds at the present time. The notions of baryon and of lepton number conservation would have to be abandoned. These are notions which are in agreement with considerations but in disagreement with the fact that proton decay has not yet been found.

THE CHRISTOLOGICAL ORIGINS OF NEWTON'S FIRST LAW

STANLEY L. JAKI

For now a hundred years the awarding of Nobel Prizes has been a major annual event. To the consternation of many the Prize in physics for 2000 did not go to theoretical physicists but to physicists whom the media quickly described as mere engineers. Herbert Kroemer, Zhores I. Alferov, and Jack S. Kilby received the Prize for making possible the Internet, which is surely a great engineering feat. It is transforming not only the world of communications, but the world itself. The number of Internet users stands today over a billion and is rapidly growing.

Whether engineers or not, the inventors of the Internet must have known a great deal about the theory which explains the motion of electrons in integrated circuits. It is another matter whether in making their invention, they had thought of the laws which govern all physical motions. In walking around in a building we hardly ever think of the foundations. Nor do we think of those who first laid such foundations that alone are capable of carrying ever larger constructions over them.

In the ever vaster edifice which is physics, Newton's three laws constitute the kind of foundations on which, and on which alone, one can safely build. The *Principia*, which is by far the most important single work in physics, is the unfolding of the contents of those three laws. Those three laws, especially the third law known as the law of force, supports all classical mechanics, all of general relativity, and is implicit in the Schrödinger equation, which is the basis of all quantum mechanics.

Newton merely hinted that he may not have been the first in every respect in laying those foundations. He never went beyond stating, and then only in private correspondence, that if he had seen further it was only "by standing on the shoulders of giants."[1] Certainly striking is Newton's silence about those giants in the *Principia*. Much less would one find out from Newton that the statement about giants and standing on their shoulders had by then been at least five hundred years old. It was, so it seems, first used by Bernard of Chartres, who was quoted in the *Metalogicon* of John of Salisbury, the rector of the cathedral school of Chartres, and later bishop there.[2]

Newton stood on the shoulders of some giants even with respect to that stroke of genius, which is the third law, or the law of force. For the third law, or more generally Newton's idea of a central field of force, is inconceivable without Kepler's three laws, and without Galileo's demonstration of the time's squared law of free fall. Newton said nothing about the fact that his second law, that action equals reaction, came from Descartes. In old age Newton spent much time in erasing in his manuscripts references to Descartes. Newton's effort to turn Descartes into a non-entity should seem all the more ridiculous because several of the Queries in Newton's *Opticks* could have been taken verbatim from Descartes' *Principes de la philosophie*. It was that work, or rather its doctrine of vortices, which the *Principia* wanted to discredit and rightly so.

But this left intact Newton's debt to Descartes in regard to the first law, or the law of inertial motion. If pressed, Newton might have perhaps referred to Descartes. It is, however, almost certain that Descartes would not have admitted that the first law, or the law of inertial motion, was not entirely his brainchild. When it comes to pride, Descartes was even more overweening than were Galileo and Newton. The century of genius was full of hubris. It was also the century that first saw the appearance of the expression "medium aevum." The context was Etienne Rausin's history, or *Leodium*, of the cathedral and diocese of Liège, published in 1639.[3] Of course, Rausin merely developed a trend that started with the humanists who by then for more than a century had distinguished classical Latin style from the "media" and "infima" Latin style, or Latinitas.

---

[1] Letter to Robert Hooke. Feb. 5, 1676. in H. W. Turnbull (ed.), *Correspondence of Isaac Newton* (Cambridge University Press, 1959), vol. I, p. 416.

[2] See *The Metalogicon of John of Salisbury: A Twelfth-Century Defense of the Verbal and Logical Arts of the Trivium*, tr. with an Introduction and Notes by D. D. McGarry (Berkeley: University of California Press, 1955), p. 167 (Bk. III, ch. 4). John of Salisbury died in 1180.

[3] *Leodium ecclesiae cathedralis, sive de dominio, regalibus, mero, mixtoque imperio . . . libri duo* (Namurci: typis Ioannis van Nilst, 1639), 643pp. The expression occurs on p. 103.

It took another fifty years before the expression appeared in the title page of a book, and of a textbook at that. The title reads "Historia medii aevi a temporibus Constantini Magni ad Constantinopolim a Turcis captam deducta," Or "The history of the Middle Ages narrated from Constantine the Great to the capture by the Turks of Constantinople" (1688).[4] The author was a German, Christopher Cellarius, or Keller. The German "Mittelalter" did not appear until 1725, and did so in a book which, though written in German, still carried the expression "medium aevum" on its title page.[5] The Académie Française approved of the term Moyen Age only in 1835, a term which did not become popular until used by Balzac and Victor Hugo. Such is at least the information one can gain from *Le Grand Robert*.[6] According to *The Oxford English Dictionary* the word "medieval" first appeared in 1827.[7] As late as the early 20th century, a Belgian author of books on the Middle Ages still thought that lexicographers would soon recommend that the terms "Moyen Age" and "médiéval" be discarded.[8] If ever there was a wrong prognostication, this was it.

While those terms were and still are often used in a pejorative sense, the centuries immediately preceding the Renaissance were not invariably held to be dark ages. In his famous *Esquisse d'un tableau historique des progrès de l'esprit humain* (1795) Condorcet praised the scholastics for having worked out indispensable principles for rational discourse.[9] Auguste Comte

---

[4] Published in Jena, the book was one in a series of textbooks on history by Cellarius (1638-1707).

[5] *Historie der römischen Huren-Regiments der Theodorae und Maroziae*...was the beginning of the long title of the work, written by the Lutheran controversialist Valentin Ernst Löscher (1674-1749) and published in Leipzig in 1705, a title which certainly foreshadowed the pejorative meaning eventually attached to the words "medieval" and "Middle Ages."

[6] Second edition (Paris: 1986), Tome VI, p. 628. There is no reference there to Auguste Comte, which indicates that he proposed and expounded his doctrine of the law of three phases without using the expressions "Moyen âge" or "médiévale."

[7] See 2nd ed. (1989), vol. IX. p. 542. Much earlier was the first appearance of "Middle Ages." See *ibid.*, p. 743. In *Merriam Webster*, which mainly considers the American usage, 1827 is given for the first appearance of "medieval" and 1840 for "Middle Ages."

[8] Godefroid J. F. Kurth (1847-1916), *Qu'est-ce que c'est le moyen age?* (Paris: Bloud, 1905). See the article "Middle Ages" by Victor Day in *Catholic Encyclopedia*, vol. XI (New York: The Gilmary Society, 1911), p. 501.

[9] See the Seventh Stage in *Sketch for a Historical Picture of the Progress of the Human Mind*, tr. J. Barraclaugh, with an introduction by S. Hampshire (New York: The Noonday Press, 1955), p. 95.

too thought that the age of positive or scientific reason had to be preceded by a metaphysical age, which, in his view, was a great improvement on the age of mythology. Comte and the positivists even praised the medieval centuries for their accomplishments in social organization and architecture. The 19th century was the age of neogothic style, yet no one, however sympathetic to the Middle Ages, would have thought that some scientific achievements too might be found there. Pierre Duhem did not expect at all to find the origins of Newton's first law in medieval centuries as he tried to present the full history of the principles of rational mechanics in his book *L'Evolution de la mécanique*, first published in 1903.[10]

When, two years later, Duhem stumbled on the contrary evidence, he should not have been so surprised. After all, since the celebration in 1873 of the 400th anniversary of Copernicus' birth, many read Copernicus' way of coping with the physical problems created by the earth's twofold motions, especially by its rotation. Although Copernicus indicated at least qualitatively the rotational speed of a point at middle latitudes, he showed no anxiety over the dynamical problem thus created.

There was, of course, some problem. In view of that speed, bodies, such as clouds in the air, should have fallen behind. To cope with this problem Copernicus first presented an answer in terms of the traditional or Aristotelian explanation of motion, that is, in terms of the nature of bodies that prompts them to occupy their natural place: "What would we say about the clouds and the other things floating in the air, or falling or rising up, except that not only the Earth and the watery element with which it is conjoined are moved in this way but also no small part of the air and whatever other things have a similar kinship with the Earth? Whether because the neighboring air, which is mixed with earthly and watery matter, obeys the same nature as the Earth [?]."[11]

Here Copernicus should have pointed out that only by contradicting the Aristotelian explanation of motion could one attribute to the air the same propensity as possessed by the water and the earth, that is, the so called heavy elements. Possibly Copernicus thought that this would be clear to most of his readers and that they did not care much for the fact that according to Aristotle it was in the nature of the air to move away

---

[10] Paris: Joanin, 1903. See also my *Uneasy Genius: The Life and Work of Pierre Duhem* (Dordrecht: Nijhof, 1984), pp. 179-80.

[11] *On the Revolutions of the Heavenly Spheres* (Great Books of the Western World, 16; Chicago: Encyclopaedia Britannica, 1952), p. 519 (Bk. I, ch. 8).

from the earth's surface. The point to watch is, however, Copernicus' conviction that he could expect his readers to be already accustomed to a very different idea of motion. Here are his words about this new idea: "or because the movement of the air is an acquired one, in which it participates without resistance on account of the contiguity and perpetual rotation of the Earth [?]."[12]

If there is no kinship or same nature, in which properties or qualities of bodies come naturally, they must acquire, and this is the word used by Copernicus, those qualities in some extraneous way. He also refers to the absence of resistance. Now to anyone aware of the difference between the Aristotelian theory of motion and Newton's laws of motion, very striking should seem Copernicus' idea about an acquired motion on earth that goes on because there is no resistance. But to anyone aware of historical research carried out by Duhem a century ago, there is no need to explain why Copernicus puts forward that idea of acquired motion without feeling the need to give an explanation.

That research brought out the fact, totally unheard of in the first decades of the 20th century, that the typical explanation of the novelty offered by Copernicus did not lie in the fact that he was a genius. Surely, it is always easy to assume that someone is a genius and then dispense with serious investigations. At that time it was all the easier to handle the problem with a reference to Copernicus' genius because even in respect to the heliocentric ordering of planets Copernicus did not mention Aristarchus of Samos as his remote predecessor. Few made much of the circumstance that Copernicus crossed out the name of Aristarchus in the manuscript of *De Revolutionibus* which Rheticus saw through press. And nobody, except Duhem, paid attention to that acquired motion.

Duhem indeed found that Copernicus himself stood on the shoulders of giants. They were Johannes Buridanus, professor at the Sorbonne and his disciple, Nicole Oresme, who subsequently became bishop of Lisieux. As a student in Cracow around 1490, Copernicus learned natural philosophy or physics from Buridan's commentaries on Aristotle's *De coelo* or *On the Heavens*. By then those commentaries had been about a century and a half old, available in many copies in medieval universities all over Europe. Even today there are about a dozen copies of those commentaries in Cracow. A reason for this is the fact that professors in those universities had very often been former students at the Sorbonne where the number of students was

---

[12] *Ibid.*

about sixty thousand or so in Buridan's time. Paris at that time was the unrivalled capital of learning.

In those commentaries the first law appears in the form of the impetus theory, or the idea that in order to produce motion it is enough to give an impetus or push to a body and have it thereby move by itself. Buridan illustrates the idea with a reference both to terrestrial motions and to the motion of the celestial bodies. In the texts that follow the gist of the impetus theory is given in italics, so that it may stand out in its context which remains, of course, very important if one is to appreciate its novelty and the source of that novelty. The text, which I will quote in English, first appeared in print in the original Latin and in French translation in 1913, in the third volume of Duhem's epoch-making work *Etudes sur Léonard de Vinci, ceux qu'il a lus et ceux qui l'ont lu*. Duhem's full-scale discussion of the topic, in the sixth and seventh volumes of his *Système du monde* should have appeared in 1917 and 1918, but they did not see print until forty years later. They finally were printed because Louis De Broglie, the discoverer of the wave nature of matter and Perpetual Secretary of the Académie des Sciences in Paris, refused to tolerate any longer an anti-Duhem conspiracy in Paris and threatened the publisher Hermann, which was part of that conspiracy, with a law suit.[13]

But back to Buridan's passages as they stand in English translation in Marshall Clagett's *The Science of Mechanics in the Middle Ages*.[14]

> [The impetus then also explains why] *one who wishes to jump a long distance drops back a way in order to run faster, so that by running he might acquire an impetus which would carry him a longer distance in the jump*. Whence the person so running and jumping does not feel the air moving him, but [rather] feels the air in front strongly resisting him.
>
> And you have an experiment [to support this position]: *If you cause a large and very heavy smith's mill [i.e., a wheel] to rotate and you then cease to move it, it will still move a while longer by this impetus it has acquired*. Nay, you cannot immediately bring it to rest, but on account of the resistance from the gravity of the mill, the impetus would be continually diminished until the mill would cease to move. And if the mill would last forever without some diminution or alter-

---

[13] See my *Reluctant Heroine: The Life and Work of Hélène Duhem* (Edinburgh: Scottish Academic Press, 1992), p. 236.

[14] Madison: The University of Wisconsin Press, 1961, pp. 524 and 536.

> ation of it, and there were no resistance corrupting the impetus, the mill would be moved perpetually by that impetus.

Buridan amplifies his first example with a reference to what may appear a very strange notion, but was not strange to Aristotle or to those who were raised on Aristotle. The notion, of which more later, is the notion of *antiperistasis*, or the idea that the body moves forward because the air which it separates as it moves forward flows past it, and then closes in behind it and acts thereby as a propellant.

In the second example, which is about the moving of a smith's wheel, or in modern terms a flywheel, Buridan amplified on motion by impetus with a clear reference to the role of resistance and also to the idea of perpetual motion. In other words, he states nothing less than that in the absence of resistance the motion would go on undiminished. But unlike the motion of a long jumper, which is more or less linear, the wheel's motion is circular. It would have been too much to expect from Buridan to distinguish the two motions, that appear, almost three hundred years later, undistinguished also in Galileo's idea of inertial motion.

But Buridan's idea of inertial motion contains something far more important and decisive than the distinction between linear and circular motions or rather inertia. Most important is the idea that the mover and the moved thing need not remain in continual contact in order to make the motion of the moved thing a continued reality. Here too the novelty becomes clear if one considers it against its Aristotelian background. Again the words that carry the idea of motion by impetus, or inertial motion, are given in italics.

> Also, since the Bible does not state that appropriate intelligences move the celestial bodies, it could be said that it does not appear necessary to posit intelligences of this kind, because it would be answered that God, *when He created the world, moved each of the celestial orbs as He pleased, and in moving them He impressed in them impetuses which moved them without His having to move them any more except by the method of general influence whereby he concurs as a co-agent in all things which take place;* "for thus on the seventh day He rested from all work which He had executed by committing to others the actions and the passions in turn." *And these impetuses which He impressed in the celestial bodies were not decreased nor corrupted afterwards, because* there was no inclination of the celestial bodies for other movements. *Nor was there resistance which would be corruptive or repressive of that impetus.* But this I do

> not say assertively, but [rather tentatively] so that I might seek from the theological masters what they may teach me in these matters as to how these things take place...
>
> And thus one could imagine that it is unnecessary to posit intelligences as the movers of celestial bodies since the Holy Scriptures do not inform us that intelligences must be posited. For it could be said that *when God created the celestial spheres, He began to move each of them as He wished, and they are still moved by the impetus which He gave to them because, there being no resistance, the impetus is neither corrupted nor diminished.*

The intelligences Buridan refers to come from Hellenistic writings in which Aristotelian and Neoplatonic ideas are fused together, especially as is the case in Plotinus and Pseudo-Dionysius. In the latter they appear as angels in charge of celestial bodies. Buridan rightly notes that those intelligences cannot be found in the Bible and that therefore the Christian is not obligated to take them seriously.

Buridan's reference to inclinations of bodies echoes, of course, the Aristotelian notion that bodies are propelled according to the volition proper to their nature. This notion is of Socratic origin, set forth in the *Phaedo*. There Socrates tried to overcome the mechanistic physics or rather ideology of the Ionians which left no room for purpose and free will. That mechanistic philosophy was dirty bathwater containing the baby, or the nascent quantitative physics. It would have been too much to expect from Socrates to distinguish between the two. The entire Socratic-Platonic-Aristotelian tradition was, with respect to science, a fatally wrong move, whereby the baby was thrown out with the dirty bathwater.[15]

The reaction to the problem of purpose in the 17th, the 18th, and 19th centuries was the reverse. There purpose was thrown out in the interest of purely quantitative or mechanistic considerations. But back to Buridan, or rather to the theological matrix of his impetus theory or idea of inertial motion. While in reference to terrestrial motions it was possible to refer to another terrestrial agent that triggers the motion, in the case of celestial bodies, or the universe, this was not the case. There a Christian, like Buridan, could refer only to the Creator. This is what Buridan did, and, most naturally, with an almost explicit reference to the words of Genesis 1, "In the

---

[15] See my article, "Socrates, or the Baby and the Bathwater" (1990), reprinted in my *Patterns or Principles and Other Essays* (Bryn Mawr, PA: Intercollegiate Studies Institute, 1995), pp. 50-62.

Beginning when God made the heaven and the earth...” Far more importantly, Buridan also states that once God creates, whether bodies or their motions, He keeps those entities in existence simply by a “general influence.”

In saying this Buridan simply restated the theological distinction between two divine actions: one is creation out of nothing, the other is the conservation in existence of what has already been created. It is in this distinction, so clear in Thomas Aquinas, who wrote two generations before Buridan, that lies the idea of the autonomous character of the laws of nature or the laws of science. In the Christian theological idea of creation, and there alone, nature can be both fully created and fully autonomous at the same time. For only a God that can create out of nothing, can give an autonomous existence to something created, without having his power diminished. Hence the independence of science, which does not become an *a priori* imposition of this or that human idea on nature.

This is to be kept in mind in reading Buridan’s reference to “theological masters.” The reference is a roundabout expression of Buridan’s conviction that the theological masters would find nothing wrong with the idea of impetus or inertial motion. This is exactly what happened, in a tacit recognition of the fact the theology is not about the *how* of the motion but only about its ultimate origin or *why*. Buridan’s impetus theory found no opposition, theological or other. Clearly Buridan’s expressed something that was in full harmony with a number of implicit and explicit assumptions, or to use an expression coined in Newton’s time, with the “climate of thought.”

In Buridan’s simultaneous application of the same law to celestial and terrestrial motions one can see anticipated Newton’s view that the same law governs the motion of the moon and the fall of a stone on the earth. Buridan also anticipates Popper’s dictum that all science is cosmology. The true laws of physics, or rather the laws of true physics, must have a validity throughout the cosmos or the universe.

Of course, the motion of the earth is not a rectilinear inertial motion. But Buridan’s idea, as applied both to the celestial bodies and to various motions on earth, implies what is the very essence of inertial motion. The idea was never stated before because it was revolutionary. The idea consists in the view that it is possible to give with a single, instantaneous act a quantity of motion, or impetus (or momentum to use the modern word) to a body and that the quantity would be maintained undiminished if the body moved in a frictionless medium.

Now why is this notion so revolutionary? Not so much because nobody had said it before, but because it represents a radical break with all earlier standard thinking about motion, especially about the motion of the celestial bodies or of the heavenly sphere. To see this one should recall briefly Aristotle's ideas of motion. According to Aristotle the origin of all motion is in the motion of the heavenly sphere of the fixed stars. This motion is somehow transmitted to the planets down to the moon. The earth itself is motionless.

The transmission is not by means of some mechanism but by some desire. The farther a planet is from the celestial sphere, the less perfect is its desire for the source of motion and therefore the more irregular is its motion. The sphere of the fixed stars alone has a perfectly regular motion, or a motion with constant velocity, because it alone is in direct contact with the Prime Mover, which is not really different from the sphere itself.

Aristotle, let this not be forgotten, is a thorough pantheist. The universe for him is a living entity and divine in its upper parts. In line with this, Aristotle posits that the mechanism causing the motion of the sphere of the fixed stars is not a mechanism but a desire of that sphere for the Prime Mover.

In modern terms, there is a continual contact between the source of motion and the things moved. Now if such is the case one is in the presence of an uninterrupted application of force. Therefore, in terms of Newtonian physics the result can only be an accelerated motion. But, of course, the sphere of the fixed stars is not accelerated. It moves at constant velocity. Clearly, Aristotelian physics and Newtonian physics are poles apart.

This difference between the two can also be seen in a much less discussed remark of Aristotle about a theory of motion, called *antiperistasis*, already mentioned above. According to that theory a stone which is thrown moves through the air because it separates the air in front of it, so that the air is forced to flow past the stone. The air therefore finds a vacuum in the wake of the stone and, since nature abhors vacuum, the air quickly closes in behind the stone and acts like a moving force. One can only wish this were true. There would be much less need for gasoline to drive our automobiles, but I am afraid space travel would be impossible.

The really revealing thing in this remark of Aristotle is that he does not reject it out of hand. Why not? Because, being a very systematic thinker, he might have seen *antiperistasis* as the natural part of a much broader theory of motion. There everything was moved in terms of a continual contact between the mover and moved. This was certainly the case with Aristotle's explanation of celestial motion. The explanation well illustrated the dictum that all science is cosmology. And if one does not forget Aristotle's pantheism one may just as well say that all cosmology is theology.

This is true not only of Aristotle, Ptolemy and Plotinus, but also of Copernicus, Newton, Laplace, Einstein and especially of all those who have been the chief spokesmen of the various forms of modern scientific cosmology, the Big Bang, the steady state, and the theory of multiple universes. They would have generated far more light if they had come clean with their theologies or countertheologies.

But back to Newton, about whom Alexander Pope wrote: “Nature and Nature’s laws lay hid in night: God said: ‘Let Newton be!’ and all was light.” The real light Newton generated was his recognition that in the motion of the moon or any of the planets two kinds of motions were fused together. One was an accelerated motion, the gravitation of the body toward the center, the other was a tangential motion. In the absence of gravitation, the moon would fly away from the earth, and the planets from the sun, and they would do so along a rectilinear path.

About the origin of the force of attraction among gravitating bodies Newton had no clear ideas. He seemed to think that the gravitational and the inertial mass were the same but also that the force of gravitation was inherent in matter. It was not in the *Principia* that he rejected as absurd the idea of action at a distance. He seemed to lean toward the idea of a mechanical transmission of gravitation.

But Newton was rather clear on the origin of the inertial motion of bodies. In the Scholium, which appeared in the second edition of Newton’s *Principia*, Newton ascribes the inertial motion of planets to an act of God who carefully adjusted the measure of that inertial motion to the central force. His statement is very similar to Buridan’s statement.

Therefore if we look for the origin of that kind of exact science which is the quantitative study of the motion, the question of the origin of the idea of inertial motion should seem central. Its original appearance in Buridan’s writings, or in 14th-century Sorbonne, cannot be disputed. But the registering of a fact is not its explanation. To us moderns nothing may seem more obvious, more natural, more self-explanatory than the idea of inertial motion. Actually its formulation represents the greatest, the most decisive breakthrough in natural philosophy.

That breakthrough took place less than seven hundred years ago. In the span of man’s three-million-year-old history it happened a mere moment ago. And the novelty remains intact even in reference to the first construction of the pyramids, an extraordinary engineering feat, five thousand years ago or with the invention of phonetic writing, an even greater intellectual achievement, about that time. The question therefore rightly arises why

Buridan's breakthrough came so late? Why is science such a latecomer in human history? The answer lies with the plainly theological context of the first appearance of that first law of motion.

There is nothing speculative about the fact that Buridan's dictum is in a clear theological context. It is the context of the doctrine, for Buridan a dogma, of creation out of nothing and in time. For him, in all evidence a genuine Christian believer, that doctrine was a dogma, defined in the fourth Lateran Council in 1215. Of course, the Council merely defined a long standing belief. Already around 200 A.D., Tertullian insisted that the Christian doctrine of creation is a doctrine about creation out of nothing, or else the Creator would be in need of some pre-existing matter. Such a pre-existing matter was invariably postulated in all the gnostic distortions of early Christian beliefs, such as a book by the gnostic Hermogenes, whose illogicalities Tertullian exposed.[16]

Equally ancient was the conviction of genuine Christians that the past history of the universe is strictly finite. This is what is meant by creation in time. They may or may not have understood the biblical phrase, "In the beginning" or *bereshit*, which, after all, is an anomaly in Hebrew grammar,[17] but they took that phrase to mean that there was an absolute beginning for all. It also inspired the notion that history, human and cosmic, is not a circular treadmill but a linear move toward a goal, a move best symbolized by an arrow.

The next point to be kept in mind is that Buridan's breakthrough comes in reference to Aristotelian physics or rather pantheism. Buridan knew full well that for Aristotle the universe was uncreated and eternal. Buridan was not, of course, the first medieval Christian to disagree on that point with Aristotle. But he was the first to probe into the physical manner in which that beginning might have taken place. The result was a breakthrough toward a new theory of motion, toward the eventual full or live birth of modern science.

But, one may ask, why one had to wait for Buridan or for the Christian Middle Ages for that breakthrough? Had not Aristotle's writings been widely known to Jews and Muslims for many centuries before the Christian medievals became acquainted with them from the mid 13th century on? On the Jewish side there were Maimonides and Crescas who studied Aristotle at great length. But there is nothing similar to Buridan's statement in their

[16] *Adversus Hermogenes*, available in translation in all major modern languages.

[17] *Bereshit* is neither an adverb nor a construct case.

works, including Maimonides' *The Guide for the Perplexed* and Crescas' *Critique of Aristotle.*

The same is true of the great Muslim Aristotelians, Avicenna and Averroes. They were, of course, more Aristotelian than Muslim. Neither of them believed in creation and Creator. This disbelief of theirs they carefully kept hidden for fear of their lives from the persecutions of Muslim orthodoxy. But neither does one find the idea of impetus in the writings of the truly believing branch of Muslim philosophers, such as al-Ashari and al-Ghazzali, both believers to the point of being mystics. The reason for this is that both rejected, for reasons of Muslim orthodoxy, the idea that there can be laws of nature.

The question therefore may be raised for purely historical reasons about whether there was something special in Buridan's belief in creation and Creator. That something was simply the fact that Buridan's belief was a Christian's belief. This statement may appear trivial as long as one does not recall Paul's statement that God created everything in the Son. Such was Paul's way of asserting Jesus' divinity in his Letters to the Ephesians (3:9) and to the Colossians (1:16).

Creation is a divine prerogative. If therefore the work of creation is assigned to Jesus, he, in Paul's eyes, has to be God. Twelve hundred years later Thomas Aquinas said nothing new when he stated in the *Summa theologiae* that though God's power is infinite, he cannot invest any creature, however eminent, with the power to create.

Let me add one more datum, but simply as a historical fact or rather a sort of cultural thought experiment. Imagine that you live in the time of Plutarch who died around 120 A.D. Assume further that Plutarch had a Christian friend, perhaps from the wider senatorial clan of the Anicii. Assume further that this friend of Plutarch's suggested to him that he read John's Gospel which by then had been widely available. A fragment of a copy of it can with certainty be dated to about 120 A.D. It contains parts of the phrase, "And Pilate asked Jesus: Are you a king?" The other side of the fragment contains recipes for cooking.

So let us assume that Plutarch, once a chief priest in Delphi, begins to read John's Gospel. He would have stopped reading it with the first chapter. For there he would have read the phrase about a mere Jew, Jesus of Nazareth, that he was the only begotten or *monogenes* son of the Father. Now Plutarch, thoroughly familiar with the entire classical tradition, knew full well that in that tradition the word *monogenes* was used in two senses. One was the trivial daily sense about the only son of a father. The other was a cosmological sense. *Monogenes* meant also the cosmos or the universe in the writings of Plato, Cicero and others, including Plutarch himself.[18] In that sense the universe was the first emanation and the only universal emanation from the First Principle which in turn was not different from the universe. This doctrine found a fully cosmological elaboration in Plotinus' *Enneads* around 250 A.D.

Plutarch therefore would be faced with a decision: if he accepts Christ as the *monogenes,* he has to stop considering the universe as the *monogenes*. The choice was not a question of mere semantics. The choice was and still is a choice between Christian monotheism and pantheism. The choice cannot be evaded by replacing pantheism with panentheism, unless one clearly states that panentheism still means creation out of nothing and in time and not a gradual emergence from the first cause or principle. But this is the kind of statement which is skirted by most champions of panentheism nowadays.

Still something is to be said of the pantheism that dominated not only ancient Greece and Hellenistic culture, but all the great ancient cultures, especially India and China. It should be easy to imagine how different history would have become if Buridan's breakthrough had occurred there and not in the Christian West. Today a maharajah might reside in a palace, where Buckingham Palace, or the Elysée Palace, or the White House stands nowadays. What could be true of a maharajah, might also be true of a mandarin.

So much in a nutshell about the most ignored and most crucial question of the history of science. The question has two sides to it. One is the invariable stillbirths of science in all ancient cultures.[19] All of them could boast of great intellects and of great technical achievements. But science, which is the science of motion, they failed to come up with. If it is true that all science is cosmology, then the ultimate reason for that failure is to be looked for in the pantheistic cosmologies that dominated all those cultures in the form of the idea of eternal returns. The swastika was its invariable symbol, which in turn implied a circle, which, because all points of it were equivalent, could not inspire the idea of an absolute start.

The other side of the question is not merely monotheism of which the idea of creation out of nothing is a strict corollary. If one considers the fact

---

[18] The major references are in Kittel's *Theologisches Wörterbuch zum Neuen Testament*, under *monogenes*.

[19] For details see chapters 1-6 in my *Science and Creation: From Eternal Cycles to an Oscillating Universe* (Edinburgh: Scottish Academic Press, 1974; 2nd enlarged edition, 1987).

that the actual forms of monotheism—Jewish, Christian and Muslim—are rooted in the same revelation given to Abraham at a given point in the past, it is possible to see a natural connection between the idea of creation out of nothing and the idea of creation in time. The latter, of course, simply means that the past history of the universe is strictly finite. Neither of those ideas can be proved or disproved by science. Science can no more specify the truly first moment of cosmic existence than it can prove the eternity of the universe. There is no measurement either of the nothing or of eternity.

But if one considers the fact that neither the Jewish nor the Muslim sages were able to come up with the true form of the science of motion, but only Christian scholars could do this, then one has to look beyond mere monotheism to Christian monotheism. As pointed out above, Christian monotheism is riveted in belief in Jesus in whom the Father created all. In other words, Christ would also loom large as the Savior of science, a point worth pondering in this year 2000.[20]

Regardless of the merit of this conclusion, the question remains about the origin of science, the most fundamental and least discussed question about science itself. One may be in error about giving a specific answer, and there have been some patently erroneous ones, which I discussed over twenty years ago in a series of lectures given at Oxford.[21] Those very wrong answers date mostly from the 18th and 19th centuries. Silence about the question has been almost total during the 20th century, which, in view of the vast evidence made available by Duhem, is inexcusable.

At any rate, truth comes out much sooner from saying something erroneous than from saying nothing or from resolutely refusing to acknowledge that there is a question, and a most serious one. It is simply not enough to say that those origins are medieval. And it flies in the face of the historical and scientific method when escape from the weight of that medieval provenance is sought in the facile remark that Buridan's insight would have come anyhow.[22] The *anyhow* is an easy escape from the clutches of the *how* and of the *why*. Of these two words, the *how* keeps science on the move, the other, the *why*, keeps the human intellect alive in the broadest sense, and makes thereby possible science as well.

[20] A point which I fully developed in my Wethersfied Institute lectures, *The Savior of Science* (1988; 2nd entirely reset edition, Grand Rapids, Michigan: Eerdmans, 2000).

[21] *The Origin of Science and the Science of its Origin* (Edinburgh: Scottish Academic Press, 1978). French translation: *L'origine de la science et la science de son origine* (Paris: Editions ESKA, 1996).

[22] Marshall Clagett, in a personal conversation.

THE PREDICTION OF CRITICAL TRANSITIONS IN COMPLEX SYSTEMS: COLLIDING CASCADES MODEL AND REAL DISASTERS

VLADIMIR I. KEILIS-BOROK

'The reactions and the attitudes with respect to such complexity are linked between two extremes: on the one hand there is the person who identifies as the sole possible solution to the problem a meticulous treatment of every process operating on the...system; on the other hand there is the person who sees the only hope as lying in "guessing" the right equations.'
(G. Puppi and A. Speranza)

1. INTRODUCTION

One of the most important and least understood features of complex systems is *the persistent re-occurrence of abrupt overall changes*, called 'critical transitions' or 'critical phenomena'. At the applied level they are referred to as crises, catastrophes, and disasters. In this paper I will consider hierarchical dissipative complex systems, which play an important role in the global village. Among such systems are the *Earth's crust*, prone to geological disasters, which in turn trigger ecological and socio-economic catastrophes; the *economy*, prone to depressions; *society*, prone to bursts of large-scale violence; the *mega-city*, on its way to self-inflicted collapse; etc.

As in the case of the study of gravity at the time of T. Brahe and J. Kepler, the study of such systems is at the 'pre-equation stage': the heuristic search for major regularities necessary for the development of a fundamental theory. At this stage, prediction is necessary to achieve a fundamental understanding of the system, as well as to reach the practical goal of being prepared for disasters.

The problem. Complex systems are not predictable with absolute precision in the Laplacean sense. However, after a coarse-graining (averaging), the regular behaviour patterns emerge; among them are scenarios of the development of critical transitions. The problem of prediction – the focus of this paper – is then posed as a consecutive, step-by-step reduction of the time-space domain, where a critical transition has to be expected (Keilis-Borok, 1996, 1990, 1999). At each step we consider the system at different levels of averaging, in a 'holistic' approach – from the whole to details. Coarse-graining limits the accuracy of prediction, but it remains important at a practical level (Molchan, 1990, 1991, 1997).

The division into consecutive approximations is dictated by the stage-by-stage development of critical transitions (Kossobokov *et al.*, 1999). At the same time this division corresponds to the needs of disaster preparedness (Kantorovich and Keilis-Borok, 1991).

A more specific version of this problem is reviewed here. Consider the dynamics of a system. Let t be the current moment in time, m – the scale ('magnitude') of a critical transition. Given the behaviour of the system prior to t, our problem is *to decide whether a critical transition with magnitude* $m>m_0$ *will occur or not during the subsequent time interval* $(t, t+\Delta)$. In other words, we have to localise in time-space a specific singular trait of the process. This formulation is considerably different from a more traditional one – the extrapolation of a process in time. The decision rule is called *the prediction algorithm* (an example is described in 2.3.2).

The dual nature of critical transition. The phenomena precursory to critical transitions were first encountered in seismicity, where the critical transitions are strong earthquakes (Keilis-Borok ed., 1990). Mathematical modelling and the analysis of real data show that these phenomena are partly 'universal', common to complex systems with different origins. Against this background the system-specific precursors emerge.

Relevance to statistical physics. The premonitory seismicity patterns discussed below are qualitatively reminiscent of the asymptotic behaviour of a system near the point of phase transition of the second kind. However, our problem is unusual for statistical physics: we do not consider the equilibrium state but the growing *disequilibrium*, which culminates in a critical transition.

Raw data include the observable background ('static') activity of the system and the external factors affecting it. Examples of the static are small earthquakes; variations in macroeconomic indicators; flow of misdemeanors; etc. The static in hierarchical systems may include critical transitions of a smaller magnitude, which form their own hierarchy (Holland, 1995); the same phenomenon may be regarded as a part of the static for the whole system and as a critical transition for some part of the system.

Pattern recognition. Having to be heuristic, the data analysis is based on the 'pattern recognition of infrequent events' – the methodology developed by the school of I. Gelfand (Gelfand *et al.*, 1976). It allows us to overcome the complexity and imprecision of the data in situations where the data are insufficient for more traditional statistical analysis.

The performance of a prediction algorithm is quantitatively characterised by the rate of false alarms, the rate of failures to predict, and the total volume of alarms (see 2.3.2). The trade-off between these characteristics is summed up by *error diagrams*. They also provide an interface between prediction and preparedness (Molchan, 1997, Kantorovich and Keilis-Borok, 1991).

Validation: ('with four exponents I can fit the elephant', E. Fermi). Inevitably, in the absence of adequate fundamental equations there is some freedom in the design of a prediction algorithm. The validation of the algorithms, taking a lion share of the efforts, involves the following three stages:[1]

(*i*) '*Sensitivity analysis*': Retrospective check as to whether the performance is insensitive to variations in the raw data and in adjustable numerical parameters.

(*ii*) '*Out of sample*' retrospective evaluation of performance through independent data not used in the design of the algorithm.

(*iii*) *Advance prediction* – the only decisive test of a prediction algorithm.

Content. *Section 2* describes the recently developed *model of colliding cascades* propagating in hierarchical chaotic systems (Gabrielov *et al.*, 2000a, 2000b, 2001, Zaliapin *et al.*, 2001a, 2001b). This is one of the lattice models of a statistical physics type intensely used in the study of critical transitions. We here consider that specific model because it exhibits a wide set of known precursors to a critical transition (Keilis-Borok, ed., 1990, 1999) and some unknown precursors to be tested by observation. The next two sections demonstrate prediction of the real (observed) critical transitions. *Section 3* discusses earthquakes. *Section 4* deals with economic recessions and unemployment.

[1] *Each* algorithm described below was validated at the first two stages and tested by advance prediction. Hereafter this point will not be repeated, so as to avoid monotonous repetitions.

2. COLLIDING CASCADES

The model of colliding cascades (Gabrielov *et al.*, 2000a, 2000b, 2001, Zaliapin *et al.*, 2001a, 2001b) summarises the three major factors responsible for the generation of critical transitions in complex systems.

(*i*) *The hierarchical structure.* Specifically we consider the ternary tree shown in Fig. 1a.

(*ii*) ‘*Loading*’ by external sources. The load is applied to the largest element and transferred downwards, thus forming direct cascades.

(*iii*) *The ‘Failures*’ of the elements under the load. The failures start from the smallest elements and gradually expand upwards the hierarchy, thus forming inverse cascades. A broken element eventually ‘heals”, which ensures the continuous operation of the system.

Cascades are realised through the interaction of adjacent elements, as shown in Fig. 1b. Direct and inverse cascades collide and interact: loading triggers the failures, while failures release and redistribute the load. The dynamics of the model are described in Gabrielov *et al.*, 2000a.

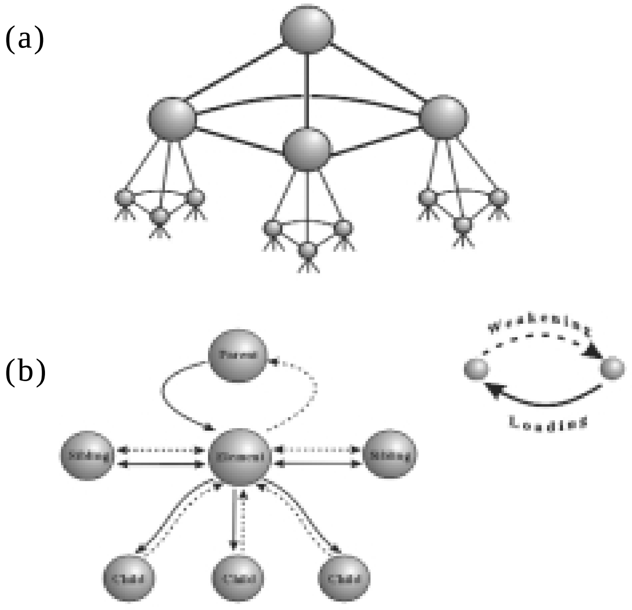


Figure 1. Structure of the colliding cascades model. a) Three highest levels of the hierarchy. b) Interaction with the nearest neighbors. [After Gabrielov *et al.* 2000b].

Fig. 2 shows an example of the sequence of failures. What is the relevance of this sequence (and of the whole model) to reality? The answer is that it fits the major heuristic constraints, derived from earthquake studies, and exhibits still unknown regularities, which can be tested through observation [acc, roc].

Separately, the cascades of each type have been intensely studied in many fields. Among classical examples are the direct cascades of eddies in the three-dimensional turbulent flow (Kolmogoroff, 1941a, 1941b, Frish, 1995), and inverse cascades in percolation (Stauffer and Aharony, 1992). Pioneering lattice models of seismicity (Burridge and Knopoff, 1967, Bak *et al.*, 1988, Allégre *et al.*, 1982) have been focused on the inverse cascades. This paper concerns a much less explored phenomenon – the *interaction* of direct and inverse cascades. It has also been considered in a model of magnetic field reversals (Blanter *et al.*, 1999).

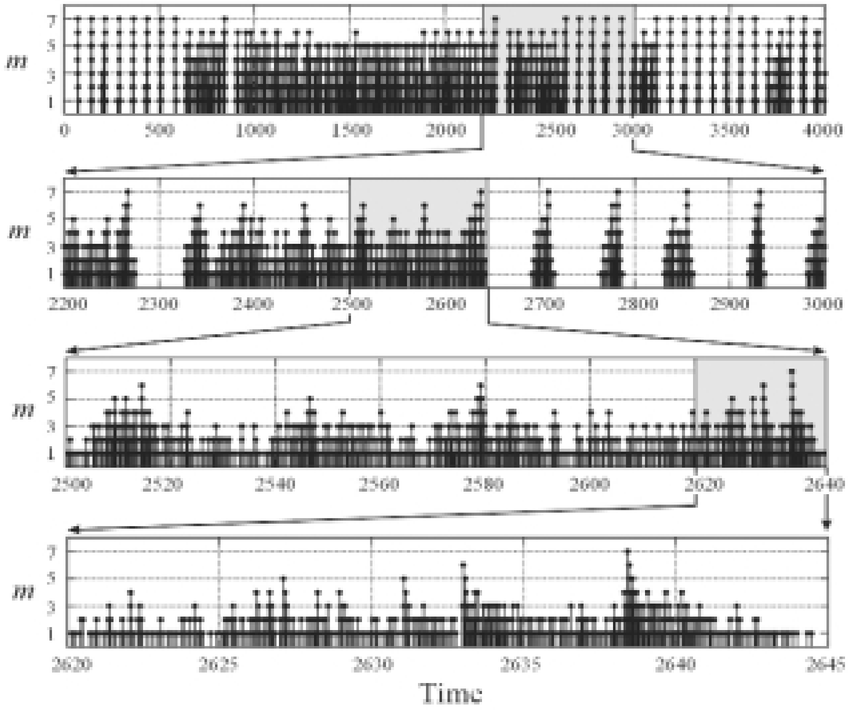


Figure 2. Synthetic earthquake sequence generated by the colliding cascades model. The complete sequence is shown in the top panel; exploded views - in the following three panels. [After Gabrielov *et al.* 2000b].

3. EARTHQUAKES

2.1. *Definitions*

To interpret colliding cascades in terms of seismicity, we associate the loading with the impact of tectonic forces, and the failures with earthquakes. The simplest standard representation of an observed earthquake sequence is

$$\{t_k,\ m_k,\ g_k\},\ k = 1, 2, \ldots \qquad (1).$$

Here, t_k is the occurrence time of an earthquake; m_k is its magnitude, i.e. logarithmic measure of energy released by the earthquake; g_k indicates coordinates of the hypocenter; and k is the sequence number of an earthquake, $t_k \leq t_{k+1}$.

Identifying the failures in the model with the real (observed) earthquakes, we regard m as the magnitude; this is a natural analogy since the size of the rupture that originates a real earthquake is strongly correlated with magnitude. The position of an element in the tree is regarded as a hypocenter; this is an admittedly coarse analogy, since, strictly speaking, the model has no Euclidean hypocenter space.

2.2. *Heuristic constrains*

Synthetic sequence of failures, shown in Fig. 2, exhibits, upon averaging, the major regular features of observed seismicity: *seismic cycles, intermittency, scale invariance, and a specific kind of clustering* (Gabrielov *et al.*, 2000a, 2000b, 2001). (The reader will recognize also a qualitative similarity with many other processes, e.g. the dynamics of an economy). In the next section we describe one more constraint, central for the problem of prediction: the set of the spatio-temporal patterns of seismicity preceding a strong earthquake.

(*i*) *Seismic cycles*. Our synthetic sequence is dominated by easily identifiable cycles, each culminating in a major earthquake. A single cycle is shown in the bottom panel of Fig. 2. It comprises three consecutive phases (Scholz, 1990): an increasing level of seismic activity culminating in one or several major earthquakes; gradual decline of activity; and period of low activity, eventually followed by the next cycle.

(*ii*) *Intermittency of seismic regime.* From time to time the sequence of cycles abruptly changes its basic features: maximal magnitude, degree of periodicity, and duration of separate cycles (compare for example three intervals: 100-500, 1000-1200 and 1500-1700 in the top panel of Fig. 2).

(*iii*) *Scale invariance*. Typically for complex systems with persistent critical transitions, the distribution of the magnitude of earthquakes follows the power law, known in seismology as the Gutenberg-Richter relation:

$$dN(m) \sim 10^{-bm}\,dm \qquad (2),$$

with the value of b being constant in considerable magnitude ranges (Gutenberg and Richter, 1954, Molchan and Dmitrieva, 1990, Turcotte, 1997, Kagan, 1999). This relation emerges after a sufficient averaging over territory and time. Fig. 3 shows that synthetic seismicity does follow this law (perhaps too perfectly); this is partly predetermined by the design of the model.

(*iv*) *Clustering*. Real earthquakes are clustered in time and space. The clustering is hierarchical, taking place in different scales. A most prominent type of clusters consists of a *main shock*, closely followed by a decaying sequence of weaker *aftershocks*. Also, about 30% of main shocks are close-

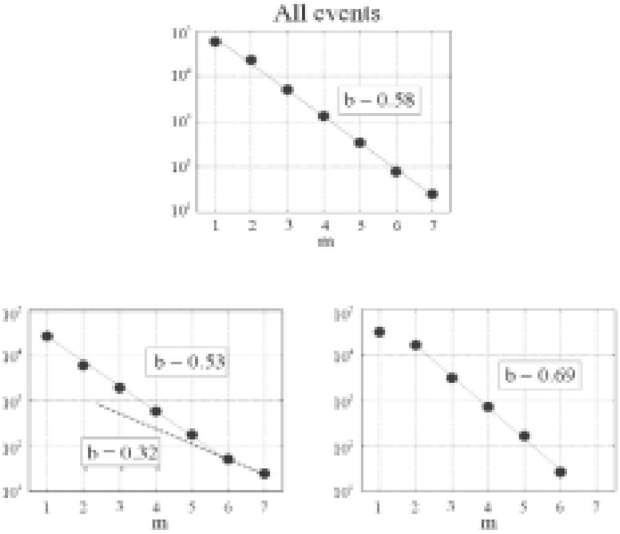


Figure 3. Magnitude distribution, log $N(m)$ = a - bm, $N(m)$ is the number of events with magnitude m. Note that the magnitude has discrete integer values from 1 to 7. a) All events. b) Main shocks. c) Aftershocks. [After Gabrielov *et al.* 2000b].

ly preceded by few weaker *foreshocks* (Molchan and Dmitrieva, 1990). The modeled sequence does exhibit the aftershocks as well as some other forms of clusters (Gabrielov *et al.*, 2000a). As in reality, the slope b in the distribution (2) is steeper for the aftershocks than for the main shocks (Fig. 3).

2.3. *Premonitory seismicity patterns*

2.3.1. Three types of premonitory phenomena. Studies of observed and modeled seismicity show that an earthquake of magnitude m_0 is preceded by certain patterns of seismicity in an area and magnitude range normalized by m_0. Specifically, these patterns reflect the following changes in seismicity (Keilis-Borok, 1994, 1996, Turcotte, 1997, Sornette and Sammis, 1995):

(*i*) Rise in the earthquakes' clustering in space and time.
(*ii*) Rise in the intensity of the earthquakes' flow.
(iii) Rise in the range of correlations between the earthquakes.

Premonitory patterns of the first two types belong to heuristic constrains for the model. They have been found mainly by the analysis of observations and are used in the intermediate-term earthquake prediction algorithms, with characteristic duration of alarms years (Keilis-Borok, ed., 1990, 1999). The third type of patterns has been found very recently in the CC model (Gabrielov *et al.*, 2000a, 2000b, 2001), although it was previously hypothesized in (Keilis-Borok 1994, 1996).

2.3.2. General scheme of prediction (Gabrielov *et al.*, 1986, Keilis-Borok, ed., 1990, Keilis-Borok and Shebalin, eds., 1999).

(*i*) *Areas.* The territory considered is scanned by overlapping areas; their size is normalised by the magnitude m_0 of the earthquakes targeted by prediction.

(*ii*) *Functionals.* An earthquake sequence in each area is described by a time function $F(t)$, depicting the premonitory changes of seismicity (see 2.3.1). Each type of change can be depicted by different functionals (for example; the clustering of the earthquakes may be measured by the generation of aftershocks and by the swarms of main shocks).

The functionals are also normalised by m_0.

(*iii*) *Premonitory patterns.* The emergence of a premonitory pattern in the area considered is recognised by the condition

$$F(t) \geq C_F \qquad (3).$$

The threshold C_F is an adjustable parameter. It is usually defined as a certain percentile of the functional F.

(*iv*) *Prediction algorithms*. An algorithm based on a single pattern is formulated as follows. Whenever $F(t) > C_F$, an alarm is declared for a time period Δ_F in the area considered. The prediction is *correct* if an earthquake with a magnitude belonging to the range (m_0, $m_0 + c$) occurs in that area and time interval; the opposite case is a *false alarm*. A *failure to predict* is the case where a major earthquake occurs outside of an alarm area and period.

Performance of an algorithm is quantitatively defined by three parameters: the rate of false alarms, the rate of failures to predict, and the total space-time, occupied by the alarms.

Most of the algorithms of that kind are based not on one but on several premonitory patterns. An alarm is declared when certain combinations of the patterns emerge (Gabrielov *et al.* 1986; Keilis-Borok, ed., 1996; Keilis-Borok & Shebalin 1999).

(*v*) *Robustness*. A highly complex process (an earthquake sequence) is described in this analysis by the few averaged functionals, which in turn are defined at the lowest (binary) level of resolution – above or below certain threshold. Predictions themselves are also binary, of a ‘yes or no’ kind, with unambiguous definition of the area and duration of alarm. The probabilistic aspect of prediction is reflected in the errors diagram, showing the tradeoff between the parameters characterising the performance of a prediction method (see item (*iv*) above).

Such robustness, usual in the exploratory data analysis (Gelfand *et al.*, 1976; Tukey, 1977), allows us to overcome the high complexity of the process considered and the chronic incompleteness of the data. This is achieved at a price, however: the limited accuracy of prediction.

2.3.3. *Application to synthetic seismicity*

The colliding cascades model reproduces the whole set of premonitory patterns described above. Prediction algorithms, based on each pattern, have been applied to synthetic earthquake sequence, as shown in Fig. 2 (Gabrielov *et al.*, 2000b). Prediction was targeted at the 25 ‘major earthquakes’, with $m = 7$. For the patterns of the first two types, depicting clustering and level of seismic activity, we used the *a priori* definitions, developed in the analysis of observations (Keilis-Borok ed., 1990). For the patterns of the new type, depicting correlation range, we used definitions developed in (Gabrielov *et al.*, 2000a).

Fig. 4 summarises the performance of these patterns. The top panel shows, in separate boxes, the emergence of the patterns before each major earthquake. The bottom panel shows the false alarms. Evidently, most of them are close to the earthquakes with a magnitude of $m = 6$.

2.3.4. *Applications to real seismicity*

Premonitory patterns of the first two kinds have been subjected to tests by advance prediction worldwide by scientists from Russia, the USA,

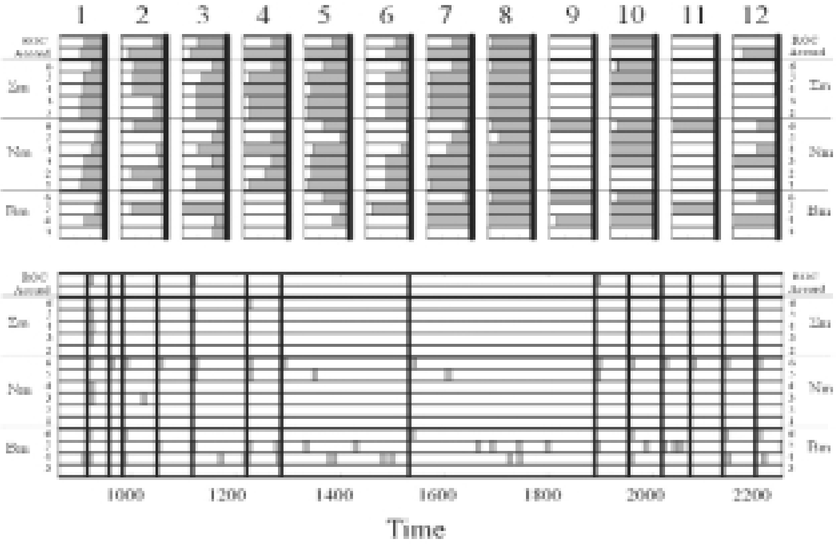


Figure 4. Collective performance of premonitory patterns. Prediction is targeted at the first 12 major events ($m = 7$) from synthetic sequence shown in Fig. 2. Figure juxtaposes alarms generated by all 17 precursors considered in Gabrielov *et al.* 2000b. The patterns *ROC* and *Accord* reflect correlation range, the patterns Σ and N – seismic activity, the pattern B – clustering (Gabrielov *et al.* 2000a, 2000b). The top panel shows, in separate boxes, emergence of precursors before each of major earthquakes in the synthetic sequence. The right edge of each box is the moment of a major earthquake. The time interval of three units is considered before each one. The bottom panel shows the alarms determined during the time periods when strong earthquakes did not occur; those are the false alarms. Vertical lines show the moments of events with magnitude $m = 6$. Evidently, $m = 6$ events are associated with most of the false alarms. Each row shows the track record of a single precursor. Shaded areas show the alarms determined by the precursor. Values of m indicate the magnitude range in which a precursor is determined. [After Gabrielov *et al.* 2000b].

France, Italy, and New Zealand; the tests, unprecedented in rigor and volume, established the high statistical significance of predictions (Molchan 1990; Kossobokov *et al.*, 1999; Vorobieva 1999; Harte *et al.* 2000 and references therein), though the probability gain is low so far, between 3 and 10. Among those predicted were 7 out of the last 8 strongest earthquakes, of magnitude 8 or more.[2]

Patterns of the third type have yet to be validated by observations. The first applications to observed seismicity, in S. California (Zaliapin *et al.* 2000) and Lesser Antilles (Shebalin *et al.* 2000), are encouraging.

Figs. 5-7 illustrate the predictions described above. Figure 5 shows successful prediction of the Sumatera earthquake $M = 8$ (Fig. 5, see p. XI). Figure 6 shows prediction of the second strong earthquake – Northridge – which followed the Landers earthquake within two years. Figure 7 depicts similarity of premonitory seismicity patterns preceding the Aquaba earthquake and a major starquake – the flash of energy radiated by a neutron star in the form of soft γ-rays repeaters (Kossobokov *et al.* 2000) (Fig. 7, see p. XI).

3. RECESSIONS AND UNEMPLOYMENT

The lattice models used in the studies of seismicity (Burridge and Knopoff, 1967; Turcotte, 1997; Rundle *et al.*, 2000; Gabrielov and Newman, 1994; Shnirman and Blanter, 1999; Huang *et al.*, 1998), the colliding cascade model included, are not necessarily specific to seismicity only. The notions central in such models – *hierarchy, loading, failures, and healing* – might be interpreted in terms of different complex processes.[3] Here, we describe the application of similar approach to socio-economic predictions (Keilis-Borok *et al.*, 2000a, 2000b; Lichtman and Keilis-Borok, 1999; Lichtman, 1996).

3.1. *American economic recessions*

Each of the five recessions which have occurred in the USA since 1962 was preceded by a specific pattern of 6 macroeconomic indicators determined in Keilis-Borok *et al.*, 2000a. This pattern emerged within 5 to 13

---

[2] Results of that test are routinely available on the website: http://www.mitp.ru

[3] Hypothetically, we encounter in the studies reviewed here an ‘arithmetic’ of critical transitions – the basic precursory phenomena, common for a wide class of complex systems. However, if that is true, the universality is not unlimited: in the background of ‘universal’ precursors the system-specific ones do emerge (Keilis-Borok, ed., 1990, 1999).

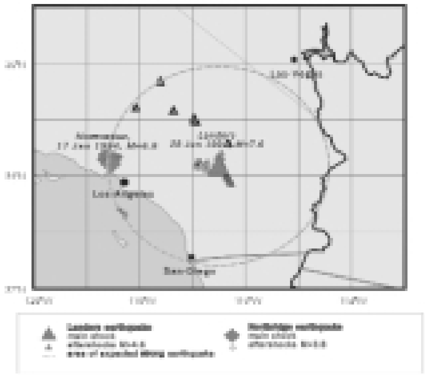


Figure 6. Prediction of the second strong earthquake. The Landers earthquake (28 June, 1992 M 7.6) was followed by the Northridge earthquake (17 January, 1994, M 6.8). The circle in the figure shows the territory, pointed by the algorithm, where occurrence of the second strong earthquake should be expected. [After Vorobieva, 1999].

months before each recession and at no other time, suggesting a hypothetical prediction algorithm. It has been put to the test by advance prediction beginning in 1996. Since then no more recessions have occurred, up to April 2001, when this is paper is being written, the algorithm has generated no alarms.

3.1.1. *Raw data.* The following routinely available monthly macroeconomic indicators have been analysed:

1. The difference between the interest rate on ten-year U.S. Treasury bonds, and the interest on federal funds on an annual basis.

2. The ‘Stock-Watson index’ of overall monthly economic activity. This is a weighted average of four measures, depicting employment, manufacturing output, and retail sales, which emphasise services.

3. The index of ‘help wanted’ advertising. This is put together by a private publishing company which measures the amount of job advertising (column-inches) in a number of major newspapers.

4. The average weekly number of people claiming unemployment insurance.

5. Total inventories in manufacturing and trade, in real dollars. This includes intermediate inventories (for example held by manufacturers, ready

to be sent to retailers) and final goods inventories (goods on shelves in stores).

6. The interest rate on ninety-day U.S. Treasury bills at an annual rate.

These indicators happen to be sufficient for prediction; other potentially relevant indicators have not yet been considered in this approach.

3.1.2. Hypothetical premonitory patterns. The premonitory behaviour of each indicator was defined (see 2.3.2) by a robust binary condition (3). An example is shown in Fig. 8a (see p. XII). It was found that the following patterns of the above indicators are premonitory, emerging more frequently as a recession approaches: a low value of indicator *1*; a strong downward trend of indicators *2* and *5*; and a strong upward trend of the three other indicators. Qualitatively, this would be expected from the nature of each indicator.

A hypothetical prediction algorithm based on these patterns generated retrospective alarms, juxtaposed with recessions in Fig. 8b (see p. XII). In the advance prediction such performance would be quite satisfactory.

Comparison with the more traditional multiregression analysis is summarised in Sect. 4 below.

3.2. *Unemployment*

Here, we summarise the study (Keilis-Borok *et al.*, 2000b) of the prediction of unemployment in Western Europe and USA. The targets of prediction are the formally defined episodes of a sharp increase in the rate of unemployment, named ‘FAUs’, ‘Fast Acceleration of Unemployment’. The FAUs in France, Germany, Italy, and USA since the early sixties have been considered. Most of them are preceded by a uniform pattern of three macroeconomic indicators. A hypothetical prediction algorithm based on these patterns is put to the test by advance prediction.

3.2.1. Raw data. The algorithm is based on the following three indicators, selected to start with from many relevant ones:

1. The industrial production index, composed of weighted production levels in numerous sectors of the economy, in % relative to the index for 1990.
2. The long-term interest rate on ten-year government bonds.
3. The short-term interest rate on three-month bills.

3.2.2. The hypothetical premonitory pattern. Most of the FAUs considered are preceded by a steep increase of all three indicators. The corresponding (hypothetical) prediction algorithm has been developed for France and then applied to Germany, Italy and USA. The alarms determined by that algorithm are juxtaposed with FAUs in Fig. 9 (see p. XII). Such results would be quite satisfactory in real time prediction, and encourage the further tests of an algorithm. So far, only one prediction, for the USA, was made in advance (Fig. 10). An alarm was determined for the period from February to November 2000 (a shaded area in Fig. 10) and unemployment did start to rise in July 2000.

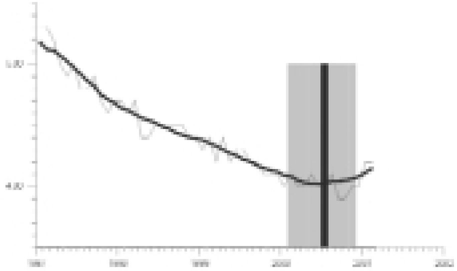


Figure 10. Unemployment rate in the U.S., July 2000: thin curve shows original data; thick curve show the rates with seasonal variations smoothed out. The gray bar shows the alarm period, defined by analysis of microeconomic indicators. The black bar – actual start of the unemployment rise, defined by analysis of monthly unemployment rates for the U.S. civilian labor force.

4. SUMMARY

1. The following findings seem promising:

– In each case the prediction rule was uniform, transcending the immense complexity of the process considered, the diversity of the prediction targets, and the change of circumstances in time. For the earthquakes, premonitory seismicity patterns happen to be similar for microcracks in laboratory samples, the largest earthquakes of the world, in the energy range from 10^{-1} erg to 10^{26} erg; possibly, also, for ruptures in a neutron star, 10^{41}erg. For recessions and unemployment, similarity overcomes the changes in the economy since 1962; in the case of FAUs, the differences between countries as well.

– Prediction was based on the routinely available data - global catalogues of earthquakes, major macroeconomic indicators, etc.

– In each case, predictability was achieved by extremely robust analysis. It is interesting to quote how an economist with an excellent track record in the prediction of recessions describes his impressions of such a robustness: ‘Prediction of recessions...requires fitting non-linear, high-dimensional models to a handful of observations generated by a possibly non-stationary economic environment...The evidence presented here suggests that these simple binary transformations of economic indicators have significant predictive content comparable to or, in many cases, better than that of more conventional models.’ J.Stock, from Keilis-Borok *et al.*, 2000a.

The accuracy of prediction is limited. However, only a small part of relevant models and available data was used, so that a wealth of possibilities for better prediction remains unexplored.

2. A similar approach was successfully applied to the prediction of president and mid-term senatorial elections in the USA (Lichtman and Keilis-Borok, 1989; Lichtman, 1996).

3. Although, obviously, neither a panacea, nor an easy ride are implied, the approaches, discussed here, open up reasonable hope that we can break the current stalemate in disaster prediction.

4. The studies summarised here involve the cooperation of about twenty institutions in twelve countries and several international projects. Still, this review is not intended to be encyclopedic and covers a specific part of the much broader effort.

Acknowledgements:

The preparation of this paper was partly supported by *The 21st Century Collaborative Activity Award for Studying Complex Systems* (James S. McDonnel foundation).

REFERENCES

1. Allégre, C.J., Le Mouel, J.L. & Provost, A., 1982. Scaling rules in rock fracture and possible implications for earthquake prediction. *Nature*, 297, 47-49.
2. Bak, P., C. Tang, and K. Wiesenfeld, 1988. Self-organized criticality. *Phys. Rev. A* 38, 364-374.

3. Blanter, E.M., Narteau, C., Shnirman, M.G. & Le Mouel, J.-L., 1999. Up and down cascade in a dynamo model: spontaneous symmetry breaking, *Phys. Rev. E*, 59, 5112-5123.
4. Burridge, R. & Knopoff, L., 1967. Model and theoretical seismicity, *Bull. seism. Soc. Am.*, 57, 341-371.
5. Frish, U., 1995. *Turbulence: The Legacy of Kolmogorov*. Cambridge University Press, Cambridge.
6. Gabrielov, A., O.E. Dmitrieva, V.I. Keilis-Borok, V.G. Kossobokov, I.V. Kuznetsov, T.A. Levshina, K.M. Mirzoev, G.M. Molchan, S.Kh. Negmatullaev, V.F. Pisarenko, A.G. Prozoroff, W. Rinehart, I.M. Rotwain, P.N. Shebalin, M.G. Shnirman, and S.Yu. Shreider, 1986. Algorithm of long-term earthquakes' prediction. *Centro Regional de Sismologia para America del Sur*, Lima, Peru.
7. Gabrielov, A. and W.I. Newman, 1994. Seismicity modeling and earthquake prediction: A review. In W.I. Newman, A.Gabrielov, and D.L. Turcotte (eds), *Nonlinear Dynamics and Predictability of Geophysical Phenomena*. AGU., Int. Un. of Geodesy and Geophys. Geophysical Monograph 83, IUGG, 18, 7-13.
8. Gabrielov, A., Keilis-Borok, V., Zaliapin, I. & Newman, W.I., 2000a. Critical transitions in colliding cascades, *Phys. Rev. E,* 62, 237-249.
9. Gabrielov, A.M., Keilis-Borok, V.I., Zaliapin, I.V., Newman, W.I., 2000b. Colliding cascades model for earthquake prediction. *JGI*, 143, 427-437.
10. Gabrielov, A. Zaliapin, I., Keilis-Borok, V., 2001. Premonitory seismicity patterns in cellular automata with colliding cascades. Manuscript.
11. Gelfand, I.M., Sh.A. Guberman, V.I. Keilis-Borok, L. Knopoff, F. Press, E.Ya.Ranzman, I.M. Rotwain, and A.M. Sadovsky, 1976. Pattern recognition applied to earthquake epicenters in California. *Phys. Earth and Planet. Inter.*, 11: 227-283.
12. Gutenberg B. and C.F. Richter, 1954. *Seismicity of the Earth and Associated Phenomena.* Princeton University Press, Princeton.
13. Harte, D., Li, D.F., Vreede, M., and Vere-Jones, D., 2000, A Model for Earthquake Probabilities Based on the M8 Algorithm. Manuscript.
14. Holland, J.H., 1995. *Hidden Order: How Adaptation Builds Complexity.* Reading, MA: Addison-Wesley.
15. Huang, Y., H. Saleur, C. Sammis, and D. Sornette, 1998. Precursors, aftershocks, criticality and self-organized criticality. *Europhys. Lett.* 41, 43-48.
16. Kagan, Y, 1999. Universality of the seismic moment-frequency relation. *Pure Appl. Geoph*. (PAGEOPH), 155, 537-573.
17. Kantorovich, L.V., and V.I. Keilis-Borok, 1991. Earthquake prediction and decision-making: social, economic and civil protection aspects. In: International Conference on Earthquake Prediction: State-of-the-Art, Strasbourg, France, *Scientific-Technical Contributions, CSEM-EMSC*: 586-593.
18. Keilis-Borok, V.I., 1994. Symptoms of instability in a system of earthquake-prone faults. *Physica D,* 77, 193-199.

19. Keilis-Borok, V., 1996. Intermediate-term earthquake prediction, *Proc. Nat. Acad. Sci. USA*, 93, 3748-3755.
20. Keilis-Borok, V.I. (Editor), 1990. Intermediate-term earthquake prediction: models, phenomenology, worldwide tests. *Phys. Earth Planet. Inter.* 61, Special Issue, 1,2: 144.
21. Keilis-Borok, V.I. and Shebalin, P.N. (Editors), 1999. Dynamics of Lithosphere and Earthquake Prediction. *PEPI*, Special Issue, III, 179-330.
22. Keilis-Borok, V., J.H. Stock, A. Soloviev, and P. Mikhalev, 2000a. Pre-recession pattern of six economic indicators in the USA. *Journal of Forecasting*, 19, 1: 65-80.
23. Keilis-Borok, V.I., A.A. Soloviev, C.B. Allègre, A.N. Sobolevskii, and M.D. Intriligator, 2000b. Patterns of macroeconomic indicators preceding the fast acceleration of unemployment in France, (manuscript).
24. Kolmogoroff, A.N., 1941a. The local structure of turbulence in an incompressible viscous fluid for very large Reynolds number, *Doklady Akademii Nauk SSSR*, 30, 299-303.
25. Kolmogoroff, A.N., 1941b. On degeneration (decay) of isotropic turbulence in an incompressible viscous fluid, *Doklady Akademii Nauk SSSR*, 31, 538-540.
26. Kossobokov, V.G., Romashkova, L.L., Keilis-Borok, V.I., and Healy, J.H., 1999, Testing earthquake prediction algorithms: statistically significant advance prediction of the largest earthquakes in the Circum-Pacific, 1992-1997. *PEPI*, 111, 187-196.
27. Kossobokov, V.G., Keilis-Borok, V.I., and Cheng, B., 2000. Similarities of multiple fracturing on a neutron star and on the Earth. *Phys. Rev. E*, 61, 4: 3529-3533.
28. Lichtman, A.J., and V.I. Keilis-Borok, 1989. Aggregate-level analysis and prediction of midterm senatorial elections in the United States, 1974–1986. *Proc. Natl. Acad. Sci. USA*, 86: 10176–10180.
29. Lichtman, A.J., 1996. *The Keys to the White House.* Lanham (ed.): Madison Books.
30. Molchan, G.M., Dmitrieva, O.E., Rotwain, I.M. & Dewey, J., 1990. Statistical analysis of the results of earthquake prediction, based on burst of aftershocks. *Phys. Earth planet. Inter.,* 61, 128-139.
31. Molchan, G.M., 1990. Strategies in strong earthquake prediction, *Phys. Earth planet. Inter.,* 61, 84-98.
32. Molchan G., Dmitrieva O, 1990. Dynamics of the magnitude-frequency relation for foreshocks. *Phys. Earth Planet. Inter.*, 61, 99-112.
33. Molchan, G.M., 1991. Structure of optimal strategies in earthquake prediction. *Tectonophysics*, 193, 267-276.
34. Molchan, G.M., 1997. Earthquake prediction as a decision-making problem. *Pure and Appl. Geophys.* 149: 233-247.
35. Rundle, D.L. Turcotte, and W. Klein (eds.), 2000. Geocomplexity and the Physics of Earthquakes. AGU, Washington, DC.

36. Scholz, C.H., 1990. *The Mechanics of Earthquakes and Faulting*. Cambridge University Press, Cambridge.
37. Shebalin, P., Zaliapin, I., and Keilis-Borok, V., 2000. Premonitory raise of the earthquakes' correlation range: Lesser Antilles. *PEPI*, 122, 3-4: 241-249.
38. Shnirman, M.G. and Blanter, E.M., 1999. Mixed hierarchical model of seismicity: scaling and prediction, *PEPI*, 111, 295-304.
39. Sornette, D., and C.G. Sammis, 1995. Complex critical exponents from renormalization group theory of earthquakes: Implications for earthquake predictions. *J. Phys. I France*, 5: 607-619.
40. Stauffer, D. and Aharony, A., 1992. *Introduction to Percolation Theory*, 2nd ed., Taylor and Francis, London, 181 pp.
41. Tukey, J.W., *Exploratory Data Analysis*, Reading, Addison-Wesley, MA, 1977.
42. Turcotte, D.L., 1997. *Fractals and Chaos in Geology and Geophysics*, 2nd ed. Cambridge University Press, Cambridge.
43. Zaliapin, I., Keilis-Borok, V., Ghil, M., 2001a. *A Boolean Delay Model of Colliding cascades. I: Multiple Seismic Regimes*. Preprint ICTP, Trieste.
44. Zaliapin, I., Keilis-Borok, V., Ghil, M., 2001b. *A Boolean Delay Model of Colliding cascades. II: Prediction of Critical Transitions*. Preprint ICTP, Trieste.
45. Zaliapin, I., Keilis-Borok, V.I., and Axen, G., 2000. Premonitory spreading of seismicity over the fault network in S. California: precursor Accord. Submitted to *JGR*, 20p.
46. Vorobieva, I.A., 1999. Prediction of a subsequent large earthquake. *Phys. Earth and Planet. Inter.*, 111, 3-4: 197-206.

CONTENTS

COMMEMORATION OF ACADEMICIANS

SELF-PRESENTATIONS OF THE NEW MEMBERS

THE PIUS XI GOLD MEDAL AWARD – SELF-PRESENTATIONS

SCIENTIFIC PAPERS

PART I: *Science for Man and Man for Science (Working Group)*

PART II: *Science and the Future of Mankind (Jubilee Session)*

TIME AND MATTER – SCIENCE AT NEW LIMITS[1]

AHMED H. ZEWAIL

INTRODUCTION

Until 1800 AD, the ability to record the timing of individual steps in any process was essentially limited to time scales amenable to direct sensory perception – for example, the eye's ability to see the movement of a clock or the ear's ability to recognize a tone. Anything more fleeting than the blink of an eye (~0.1 second) or the response of the ear (~0.1 millisecond) was simply beyond the realm of inquiry. In the nineteenth century, the technology was to change drastically, resolving time intervals into the sub-second domain. The famous motion pictures by Eadweard Muybridge (1878) of a galloping horse, by Etienne-Jules Marey (1894) of a righting cat, and by Harold Edgerton (mid-1900's) of a bullet passing through an apple and other objects are examples of these developments, with millisecond to microsecond time resolution, using snapshot photography, chronophotography and stroboscopy, respectively. By the 1980's, this resolution became ten orders of magnitude better [see Section III], reaching the femtosecond scale, the scale for atoms and molecules in motion (see Fig. 1).

For matter, the actual atomic motions involved as molecules build and react had never been observed before in real time. Chemical bonds break, form, or geometrically change with awesome rapidity. Whether in isolation or in any other phase of matter, this ultrafast transformation is a dynamic process involving the mechanical motion of electrons and atomic nuclei. The speed of atomic motion is ~ 1 km/second and, hence, to record atomic-scale dynamics over a distance of an angström, the average time required

---

[1] Adapted from the Lecture published in *Les Prix Nobel* (1999).

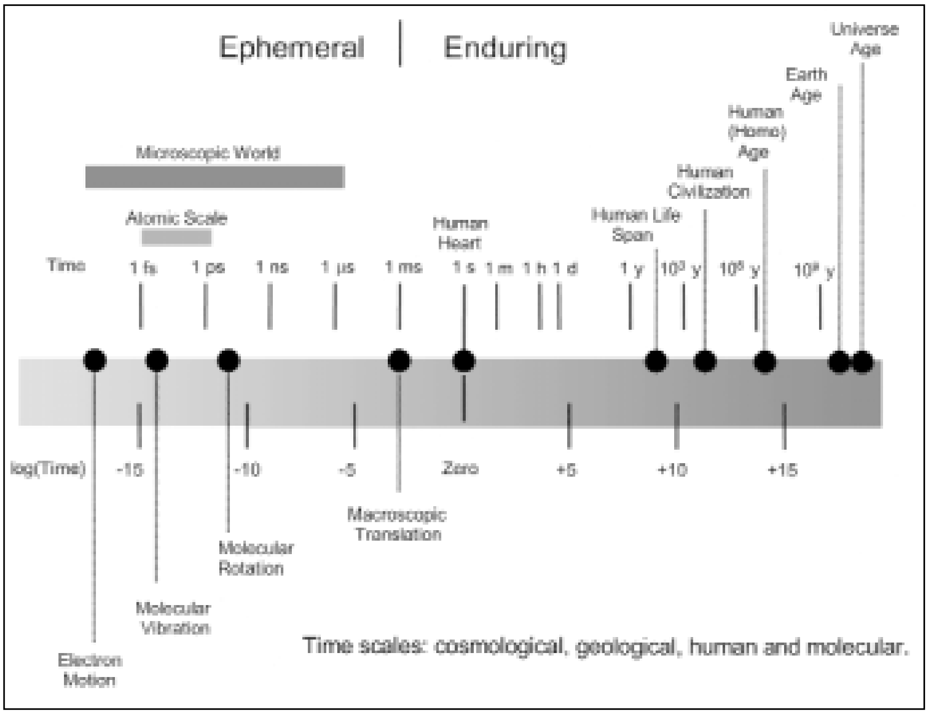


Figure 1. Time scales of cosmological, geological, human and molecular events; from the big bang to the femtosecond age.

is ~ 100 femtoseconds (fs). The very act of such atomic motions as reactions unfold and pass through their transition states is the focus of the field of femtochemistry. With femtosecond time resolution we can “freeze” structures far from equilibrium and prior to their vibrational and rotational motions, and study physical, chemical, and biological changes.

Ultrafast pulsed laser techniques have made direct exploration of this temporal realm a reality (Sections III & IV). Spectroscopy, mass spectrometry and diffraction play the role of “ultra-high-speed photography” in the investigation of molecular processes. A femtosecond laser *probe* pulse provides the shutter speed for freezing nuclear motion with the necessary spatial resolution. The pulse probes the motion by stroboscopy, i. e. by pulsed illumination of the molecule in motion and recording the particular snapshot. A full sequence of the motion is achieved by using an accurately-timed series of these probe pulses, defining the number of frames per second.

In order to study the motion, there exist three additional requirements. First, we need to *clock* the motion by defining its zero of time, also accurate to tens of femtoseconds. Second, the motion must be *synchronized* since millions of molecules are typically used in the recording of molecular motion. Third, molecular *coherence* (see below) must be induced to *localize* the nuclei. These requirements are satisfied by using a femtosecond pump (initiating) laser pulse, in what is referred to as a pump-probe configuration. For femtosecond studies, where femtosecond control of relative timing is needed, the laser pump and probe pulses are produced in synchrony, then the probe pulse is diverted through an adjustable optical path length. The finite speed of light translates the difference in path length into a difference in arrival time of the two pulses at the sample; 1 micron corresponds to 3.3 fs. The individual snapshots combine to produce a complete record of the continuous time evolution – a motion picture, or a movie – in what may be termed femtoscopy (femtosecond stroboscopy).

Applications are numerous. For example, studies in femtochemistry have spanned the different types of chemical bonds – covalent, ionic, dative and metallic, and the weaker ones, hydrogen and van der Waals bonds. In femtobiology, studies have continued to address the nature of dynamics in complex molecular systems, such as proteins and DNA. Studies have been made in the different phases of matter: gases and molecular beams; mesoscopic phases of clusters, nanostructures, particles and droplets; condensed phases of dense fluids, liquids, solids, surfaces and interfaces. New opportunities are also emerging with current interest in controlling molecular dynamics and in advancing diffraction methods for structural studies.

II. COHERENCE, DUALITY, AND THE UNCERTAINTY PRINCIPLE

The femtosecond time scale is unique for the creation of coherent molecular wave packets on the atomic scale of length, a basic problem rooted in the development of quantum mechanics and the duality of matter (Fig. 2). Molecular wave functions are spatially diffuse and exhibit no motion. Superposition of a number of separate wave functions of appropriately chosen phases can produce the spatially localized and moving coherent wave packet (Fig. 3). The packet has a well-defined (group) velocity and position which now makes it analogous to a moving classical marble, but at atomic resolution, and *without* violation of the uncertain-

Matter Waves
Particle-type Control & Dynamics

de Broglie (1924)

Einstein's light wave/particle

$E = h\nu \qquad E = cp$

$\therefore \lambda = h/p$

Similarly, matter particle/wave

Schrödinger (1926)

The Wave Equation – Stationary waves

$H\Psi = E\Psi$

Schrödinger (1926)

Micro- to Macro-mechanics
Quantum to Newton Mechanics
Ψ to wave group

Femtochemistry & Quantum Limit (h):
Particle-type

$\lambda_{\text{de Broglie}}$ (initial localization) $= h/p$
uncertainty in time measurement

$\Delta x\,\Delta p \geq h/(2\pi) \qquad \Delta t\,\Delta E \geq h/(2\pi)$

for force free
$\Delta x = p/m\,\Delta t \equiv v\,\Delta t$

$\Delta t \sim 10$ fs $\quad \Delta x \sim 0.1$ Å
$\Delta t \sim 10$ ps $\quad \Delta x \sim 100$ Å

Figure 2. Light and matter – some historical milestones, with focus on duality and uncertainty.

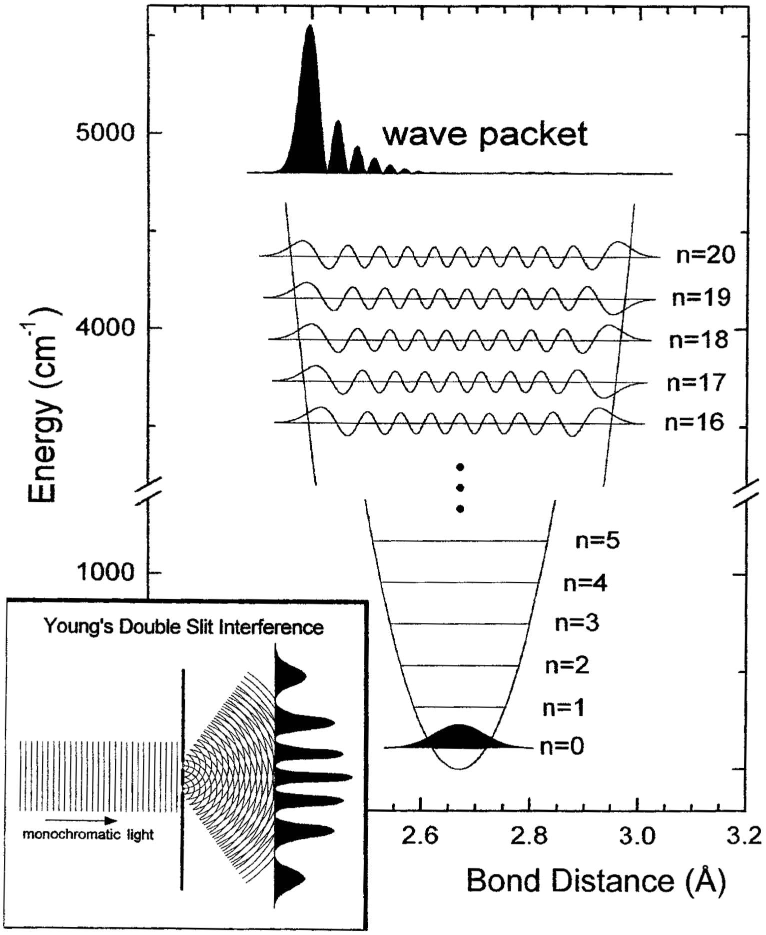


Figure 3. Coherent, localized wave packet (de Broglie length ~0.04 Å) of a diatomic molecule (iodine); 20 fs pulse. The contrast with the diffuse wave function limit (quantum number *n*) is shown. The inset displays a schematic of Thomas Young's experiment (1801) with the interference which is useful for analogy with light.

ty principle; this point regarding violation of quantum uncertainty was of major concern to many scientists and has been detailed elsewhere. As long as the wave packet (typical width ~0.05 Å) is sufficiently localized on the scale of all accessible space (~0.5 Å or more), as in the figure, a description in terms of the classical concepts of particle position and momentum is entirely appropriate. In this way, localization in time and in space are simultaneously achievable for reactive and nonreactive systems, as discussed below.

The observation of motion in real systems requires not only the formation of localized wave packets in each molecule, but also a small spread in position among wave packets formed in the typically millions of molecules on which the measurement is performed. The key to achieving this condition is generally provided by the well-defined *initial*, equilibrium configuration of the studied molecules before excitation and by the *"instantaneous"* femtosecond launching of the packet. The spatial confinement (in this case ~0.05 Å) of the initial ground state of the system ensures that all molecules, each with its own coherence among the states which form its wave packet, begin their motion in a bond-distance range much smaller than that executed by the motion. The femtosecond launching ensures that this narrow range of bond distance is maintained during the entire process of preparation, as shown below. Unless molecular and ensemble coherences are destroyed by intra- and/or inter-molecular perturbations, the motion is that of a *single-molecule trajectory* (Fig. 4).

This powerful concept of *coherence* was a key advance in observing the dynamics with atomic-scale resolution. The realization of its importance and its detection by selectivity in both preparation and probing were essential in all studies, initially of states and orientations, and culminating in atomic motions in reactions. With these concepts in mind, the marriage of ultrafast lasers with molecular beams proved to be essential for the initial development. Laser-induced fluorescence was the first probe used, but later we invoked mass spectrometry and non-linear optical techniques. Now numerous methods of probing are known and used in laboratories around the world.

III. Arrow of Time: A Century of Development

Time resolution in chemistry and biology has witnessed major strides, which are highlighted in (Fig. 5). Systematic studies of reaction velocities were hardly undertaken before the middle of the 19th century; in 1850 Ludwig Wilhelmy reported the first quantitative rate measurement, the hydrolysis of a solution of sucrose. A major advance in experiments involving sub-second time resolution was made with flow tubes in 1923 by H. Hartridge and F.J.W. Roughton for solution reactions. Two reactants were mixed in a flow tube, and the reaction products were observed

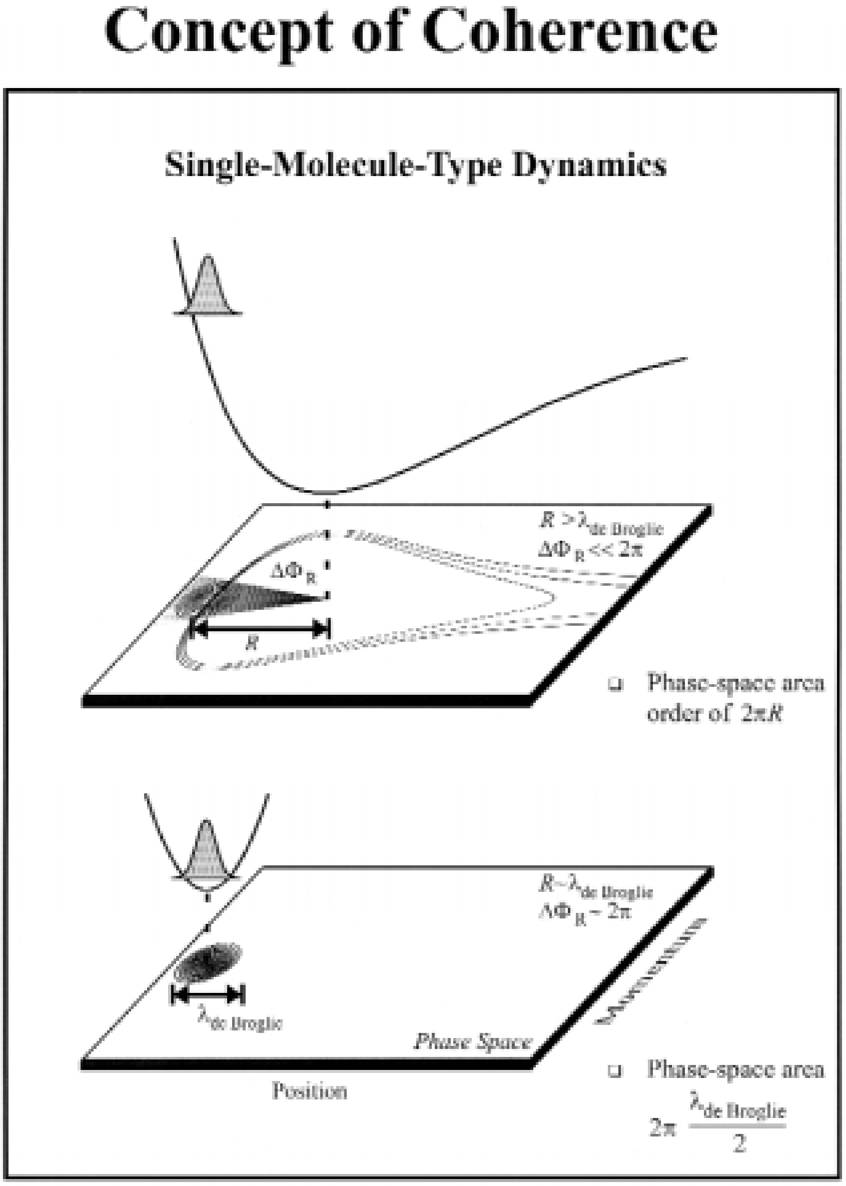


Figure 4. Concept of coherence, fundamental to the dynamics with atomic-scale resolution and in the control of reactivity. For details, see references by the author in the section, Further Reading.

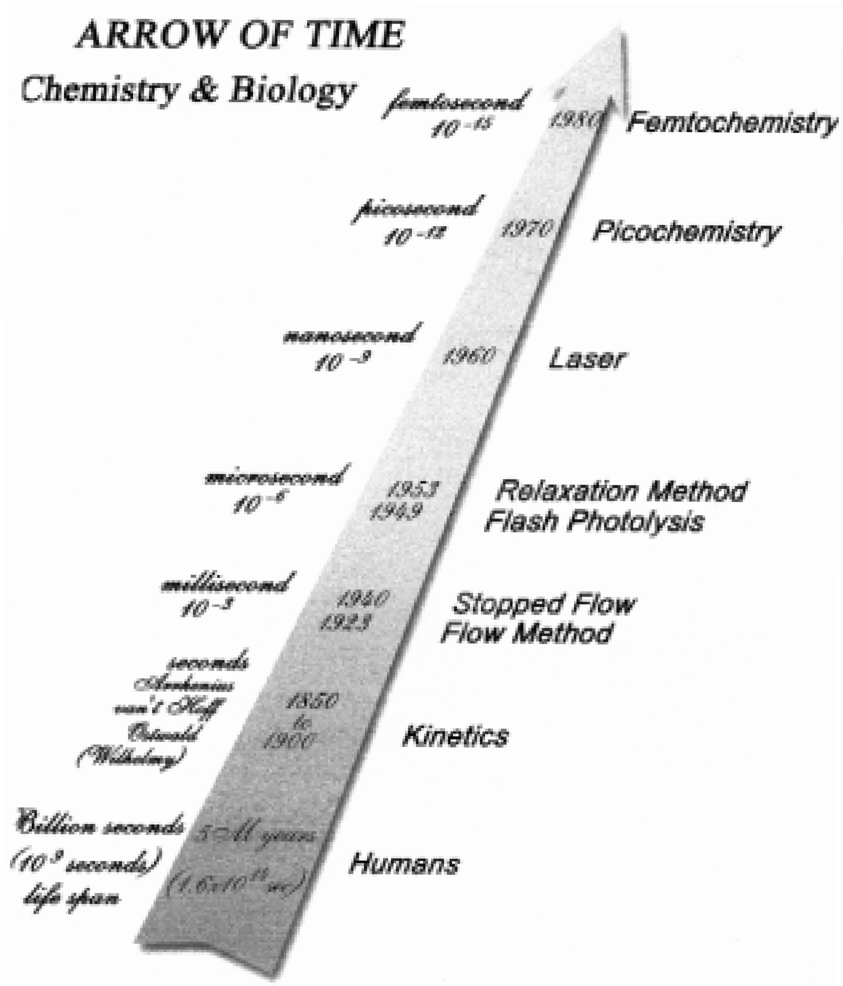


Figure 5. Arrow of Time in chemistry and biology – some of the steps in over a century of development (see text).

at different distances. Knowing the speed of the flow, one could translate this into time, on a scale of tens of milliseconds. Such measurements of non-radiative processes were a real advance in view of the fact that they were probing the "invisible", in contrast with radiative glows which were seen by the naked eye and measured using phosphoroscopes. Then came the stopped-flow method (B. Chance, 1940) that reached the millisecond scale. The stopped-flow method is still used today in biological kinetics.

Before the turn of the 20th century, it was known that electrical sparks and Kerr cell shutters could have response times as short as ten nanoseconds. In an ingenious experiment, Abraham and Lemoine (1899) in France demonstrated that the Kerr response of carbon disulfide was faster than ten nanoseconds; it has now been measured to be about two picoseconds (with fs response). They used an electrical pulse which produced a spark and simultaneously activated a Kerr shutter. Light from the spark was collimated through a variable-delay path and through the Kerr cell (polarizer, CS_2 cell and analyzer). The rotation of the analyzer indicated the presence of birefringence in the cell for short optical delays; this birefringence disappeared for pathlengths greater than several meters, reflecting the total optical/electrical response time of 2.5 ns. They demonstrated in 1899 the importance of synchronization in a pump-probe configuration. The setting of time delays was achieved by varying the light path.

Around 1950, a stride forward for time resolution in chemistry came about when Manfred Eigen in Germany and R.G.W. Norrish and George Porter in England developed techniques reaching the microsecond time scale. For this contribution, Eigen and Norrish and Porter shared the 1967 Nobel Prize. Flash photolysis utilized the above pump-probe approach, but one of the flashes was made very intense to generate high concentrations of free radicals and hence their utility in chemical and spectroscopic applications. Eigen developed “the relaxation method”, which reached the microsecond and close to the nanosecond scale. By disturbing the equilibrium of a solution by either a heat jump, a pressure jump, or an electric field, the system shifts from equilibrium. This is the point of time zero. Then the system equilibrates, and its kinetics can be followed. (At about the same time, shock-tube methods were used to provide kinetics on similar time scales.) Eigen called these reactions “immeasurably fast” in his Nobel lecture. There was a feeling that this time resolution was the fastest that could be measured or that needed to be measured for relevance to chemistry (see below). The invention of the laser has changed the picture.

Shortly after the realization of the first (ruby) laser by Maiman (1960), the generation of giant and short pulses became possible: nanoseconds by Q-switching (Hellwarth, 1961) and picoseconds (De Maria, *et al* 1966) by mode-locking (1964). Sub-picosecond pulses from dye lasers (Schäfer and Sorokin, 1966) were obtained in 1974 by Chuck Shank and Eric Ippen at Bell Labs, and in 1987 a six fs pulse was achieved. In 1991, with the generation of fs pulses from solid-state Ti-sapphire lasers by Sibbett and colleagues, dye lasers were rapidly replaced and fs pulse generation became a standard laboratory tool; the state-of-the-art, once 8 fs, is currently ~ 4 fs and made it into the Guinness Book of World Records (Douwe Wiersma's group). The tunability is mastered using continuum generation (Alfano & Shapiro) and optical parametric amplification.

In the late sixties and in the seventies, picosecond resolution made it possible to study *non-radiative* processes, a major detour from the studies of conventional *radiative* processes to infer the non-radiative ones. As a beginning student, I recall the exciting reports of the photophysical rates of internal conversion and biological studies by Peter Rentzepis; the first ps study of chemical reactions (and orientational relaxations) in solutions by Ken Eisensthal; the direct measurement of the rates of intersystem crossing by Robin Hochstrasser; and the novel approach for measurement of ps vibrational relaxations (in the ground state of molecules) in liquids by Wolfgang Kaiser and colleagues. The groups of Shank and Ippen have made important contributions to the development of dye lasers and their applications in the ps and into the fs regime. Other studies of chemical and biological nonradiative processes followed on the ps time scale, the scale coined by G.N. Lewis as the "jiffy" – the time needed for a photon to travel 1 cm, or 33 picoseconds.

IV. THE BIRTH OF THE FIELD

Stimulated by earlier work done at Caltech in the 1970's and early 80's on coherence and intramolecular vibrational-energy redistribution (IVR), we designed in 1985 an experiment to monitor the process of bond breakage (ICN* –> I + CN). The experimental resolution at the time was ~400 fs and we could only probe the formation of the CN fragment. We wrote a paper, ending with the following words: "*Since the recoil velocity is ~ 2 x 10^5 cm/s, the fragment separation is ~ 10Å on the time scale of the experiment (~500 fs). With this time resolution, we must, therefore, consider the proximity of fragments at the time of probing, i.e., the evolution of the transition state to final products.*" This realization led, in two years time, to the study of the same reaction but with ~40 fs time resolution, resolving, for the first time, the elementary process of a chemical bond and observing its transition states.

One year later in 1988, we reported on the NaI discovery which represents a paradigm shift for the field. There were two issues that needed to be established on firmer bases: the issue of the uncertainty principle and the influence of more complex potentials on the ability of the technique to probe reactions. The alkali halide reactions were thought of as perfect prototypes because they involve two potentials (covalent and ionic) along the reaction coordinate: the separation between Na and I. The resonance motion between covalent and ionic configurations is the key to the dynamics of bond breakage. *How could we probe such motion in real time?* We did the femtochemistry experiments on NaI and NaBr, and the results were thrilling and made us feel very confident about the ability to probe transition states and final fragments. The experiments established the foundation for the following reasons:

First, we could show experimentally that the wave packet was highly localized in space, ~ 0.1Å, thus establishing the concept of dynamics at *atomic-scale resolution*. *Second,* the spreading of the wave packet was minimal up to a few picoseconds, thus establishing the concept of *single-molecule trajectory,* i.e., the ensemble coherence is *induced* effectively, as if the molecules are glued together, even though we start with a random and noncoherent ensemble – dynamics, *not* kinetics. *Third*, vibrational (rotational) coherence was observed during the entire course of the reaction (detecting products or transition states), thus establishing the concept of *coherent trajectories in reactions*, from reactants to products. *Fourth*, on the fs time scale, the description of the dynamics follows an *intuitive classical picture* (marbles rolling on potential surfaces) since the spreading of the packet is minimal. Thus, a time-evolving profile of the reaction becomes parallel to our thinking of the evolution from reactants, to transition states, and then to products.

The NaI case was the first to demonstrate the *resonance behavior*, in real time, of a bond converting from being covalent to being ionic along the reaction coordinate. From the results, we obtained the key parameters of the dynamics such as the time of bond breakage, the covalent/ionic coupling strength, the branching of trajectories, etc. In the 1930's, Linus Pauling's description of this bond was *static* at equilibrium; now we can describe the *dynamics* in real time by preparing structures far from equilibrium. Numerous theoretical and experimental papers have been published by colleagues and the system enjoys a central role in femtodynamics.

The success in the studies of elementary (NaI and ICN) reactions triggered a myriad of other studies in simple and complex systems and in different phases of matter. These studies of physical, chemical, and biological changes are reviewed elsewhere (see Further Readings Section). Fig. 6 gives a summary of the scope of applications in femtochemistry, and Fig. 7 lists four general concepts which emerged from these studies. Fig. 8 highlights

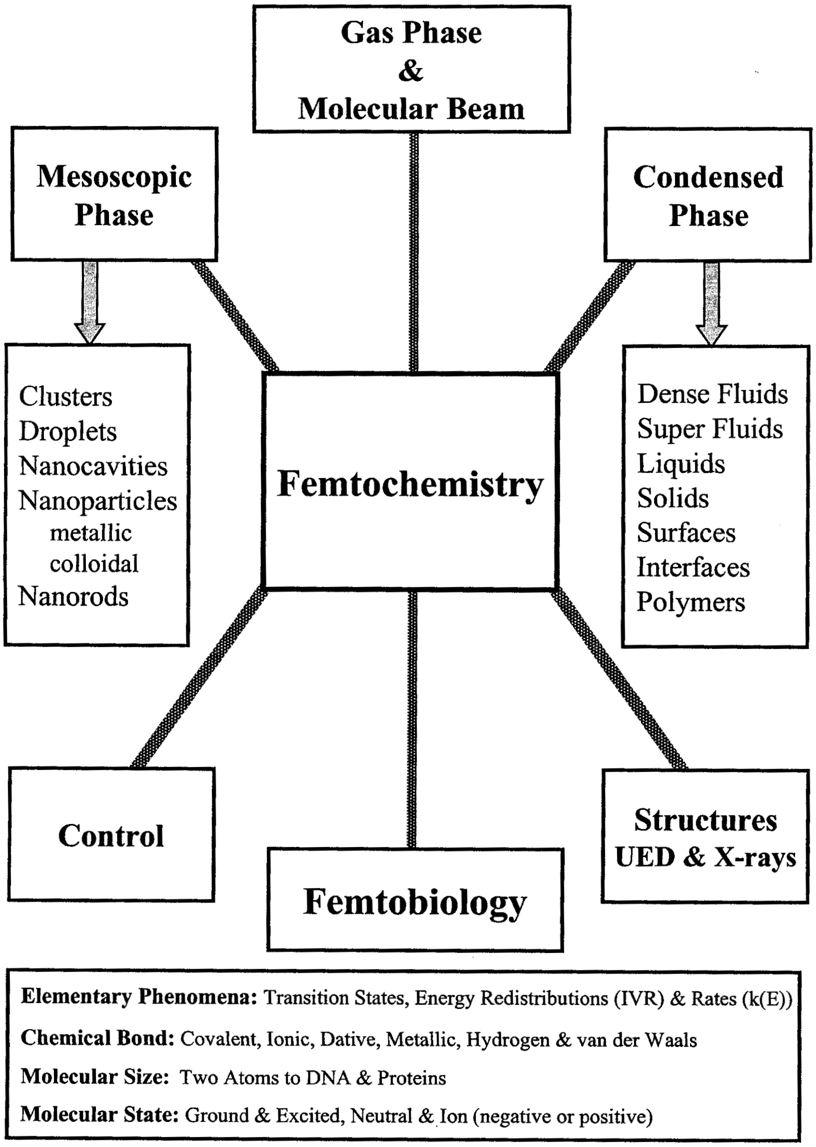


Figure 6. Areas of study in femtochemistry (and femtobiology) and the scope of applications in different phases.

Concepts

☐ **Coherence**

single-molecule dynamics

☐ **Resonance**

non-equilibrium dynamics

☐ **Transition-state Landscape**

family of structures in dynamics

☐ **Reduced Molecular Space**

directed dynamics

Figure 7. Concepts central to dynamics with femtosecond resolution. For details, see references by the author in the section, Further Reading.

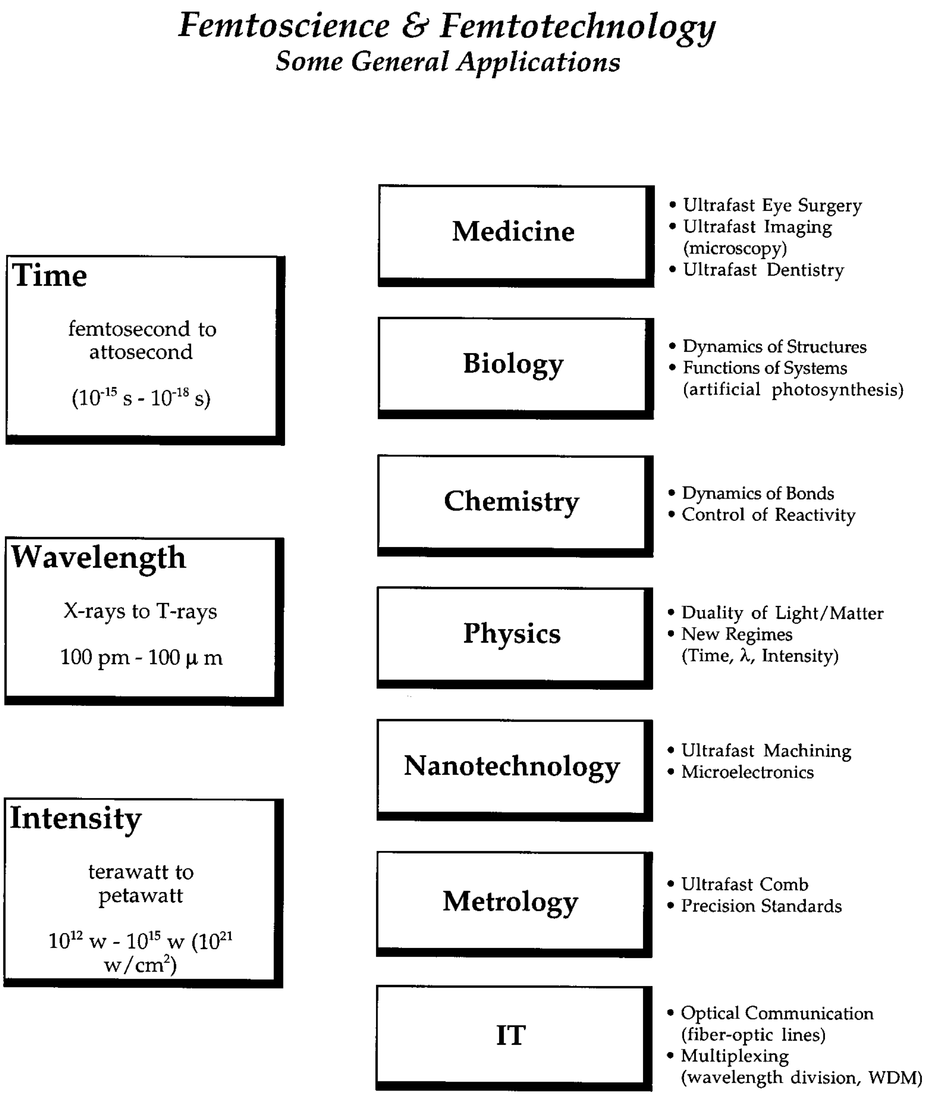


Figure 8. Some other areas of advances, from physics to medicine to technology. For reviews, see Further Reading section.

some general applications of femtoscience and femtotechnology, which are the results of advances made in new limits of time resolution, wavelength extension, and intensity or brightness (see Further Reading).

V. OPPORTUNITIES FOR THE FUTURE

Three areas of study are discussed here:

(A) Transient Structures from Ultrafast Electron Diffraction

Electron diffraction of molecules in their ground state has been a powerful tool over the past 50 years, and both electron and x-ray methods are now being advanced in several laboratories for the studies of structural changes. We have reported the latest advance in UED, by which major challenges were surmounted: the very low number densities of gas samples; the absence of the long-range order that is present in crystals, which enhances coherent interference; and the daunting task of determining in situ the zero-of-time when diffraction changes are on the ps and sub-ps time scale. The direct observation of transient structural changes in the course of a reaction was published recently in PNAS and in Science.

This leap in our ability to record structural changes on the ps and shorter time scales bodes well for many future applications to complex molecular systems, including biological systems. We have completed a new apparatus equipped with diffraction detection and also with mass spectrometry. This universal system (Fig. 9) is capable of studying complex systems in the gas and other phases. It holds great promise with opportunities for the future.

(B) Biological Dynamics

There have been important contributions to femtobiology and these include: studies of the elementary steps of vision; photosynthesis; protein dynamics; and electron and proton transport in DNA. In proteins such as those of photosynthetic reaction centers and antennas, hemoglobins, cytochromes and rhodopsin, a femtosecond event, bond breaking, twisting or electron transfer occurs. There exist global and coherent nuclear motions, observed in these complex systems, and it is possible that the complexity is not as complicated as we think. Our efforts in this direction have so far focused on DNA twisting dynamics, electron transfer in DNA assemblies, DNA base-pair models, and on protein-ligand dynamics.

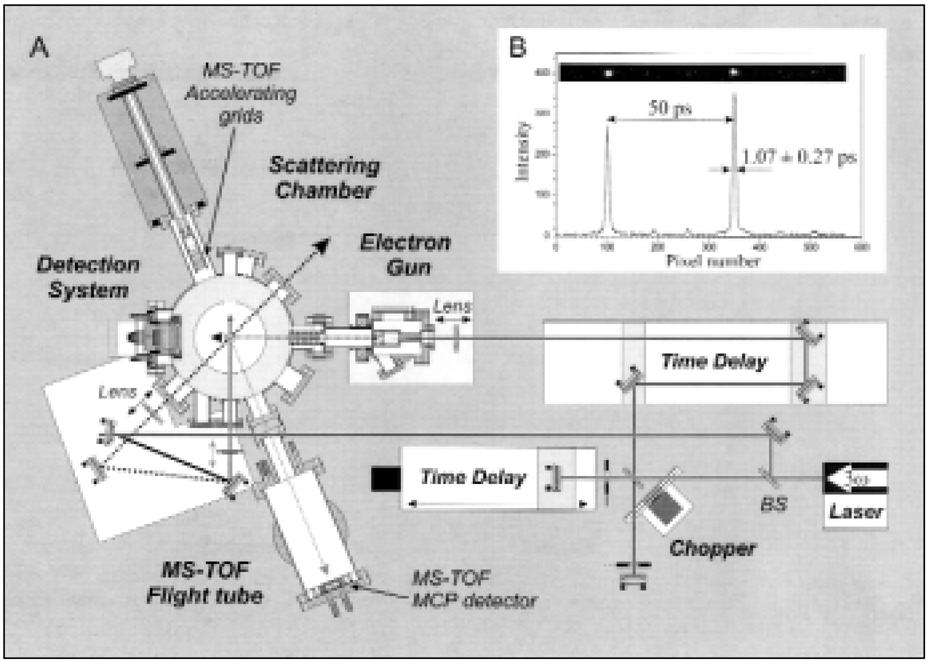


Figure 9. Ultrafast electron diffraction machine built at Caltech for the studies of molecular structures with spatial and temporal resolution on the atomic scale.

For DNA, we found that the local involvement of the base pairs controls the time scale of electron transfer. The degree of coherent transport critically depends on the time scale of molecular dynamics defining the so-called dynamical disorder. Static disorder, on the other hand, is governed by energetics. The measured rates and the distance range of the transfer suggest that DNA is not an efficient molecular wire.

For proteins, our current interest is in the studies of the hydrophobic forces and electron transfer, and oxygen reduction in models of metallo-enzymes. For the former, we have studied, with fs resolution, the protein Human Serum Albumin (HSA), probed with small (ligand) molecules. This protein is important for drug delivery. The ligand recognition is controlled by the time scale for entropic changes which involves the solvent. For model enzymes of O_2 transport, we examined novel picket-fence structures which bind oxygen to the central metal with ~ 85% efficiency at room temperature. In this system, we observed the release of O_2 in 1.9 ps and the recombination was found to occur on a much longer time scale. These are fruitful areas for future research, especially in that they provide prototype systems for O_2 reduction in the transition state at room temperature. Studies in femtobiology are continuing in our laboratory and include the recognition in protein-DNA complexes (Fig. 10).

(C) Reaction Control

Our interest in this area goes back to the late 1970's when a number of research groups were reporting on the possibility of (vibrational) mode-selective chemistry with lasers. At the time, the thinking was directed along two avenues. One of these suggested that, by tuning a CW laser to a given state, it might be possible to induce selective chemistry. It turned out that its generalization could not be made without knowing and controlling the time scales of IVR in molecules. Moreover, state-selective chemistry is quite different from bond-selective chemistry. The second avenue was that of IR multiphoton chemistry. In this case, it was shown that the initial IR coherent pumping could be used for selective isotope separation. Such an approach has proven successful, even on the practical scale, and Vladelin Letokhov has called the process "incoherent control".

In 1980, I wrote a *Physics Today* article in a special issue on laser chemistry suggesting the use of ultrashort pulses (not CW or long-time lasers) to control the outcome of a chemical reaction (Fig. 11). The title of the paper was: Laser Selective Chemistry – Is it Possible? The subtitle stated the message, *"With sufficiently brief and intense radiation, properly tuned to specific resonances, we may be able to fulfill a chemist's dream, to break particular selected bonds in large molecules."* Ultrashort pulses should be used to control the system in the desired configuration by proper choice of the *coherence time* (duration) and delay and the ability to *localize* the system in phase space.

Experimentally, we had already developed methods for the control of the phase of the field of optical pulses with the idea of using the *phase ("pulse shaping")* to control molecular processes – collisions, inhomogeneous broadenings and even photon locking which could inhibit relaxation; the time scale was ns and for the control of IVR, fs pulses were needed. Prior to this work, the optical pulse field,

$$E(t) = E_o\, A(t)\, cos[\omega t + \phi(t)],$$

was simply defined by the envelope A(t) and the frequency ω; the phase $\phi(t)$

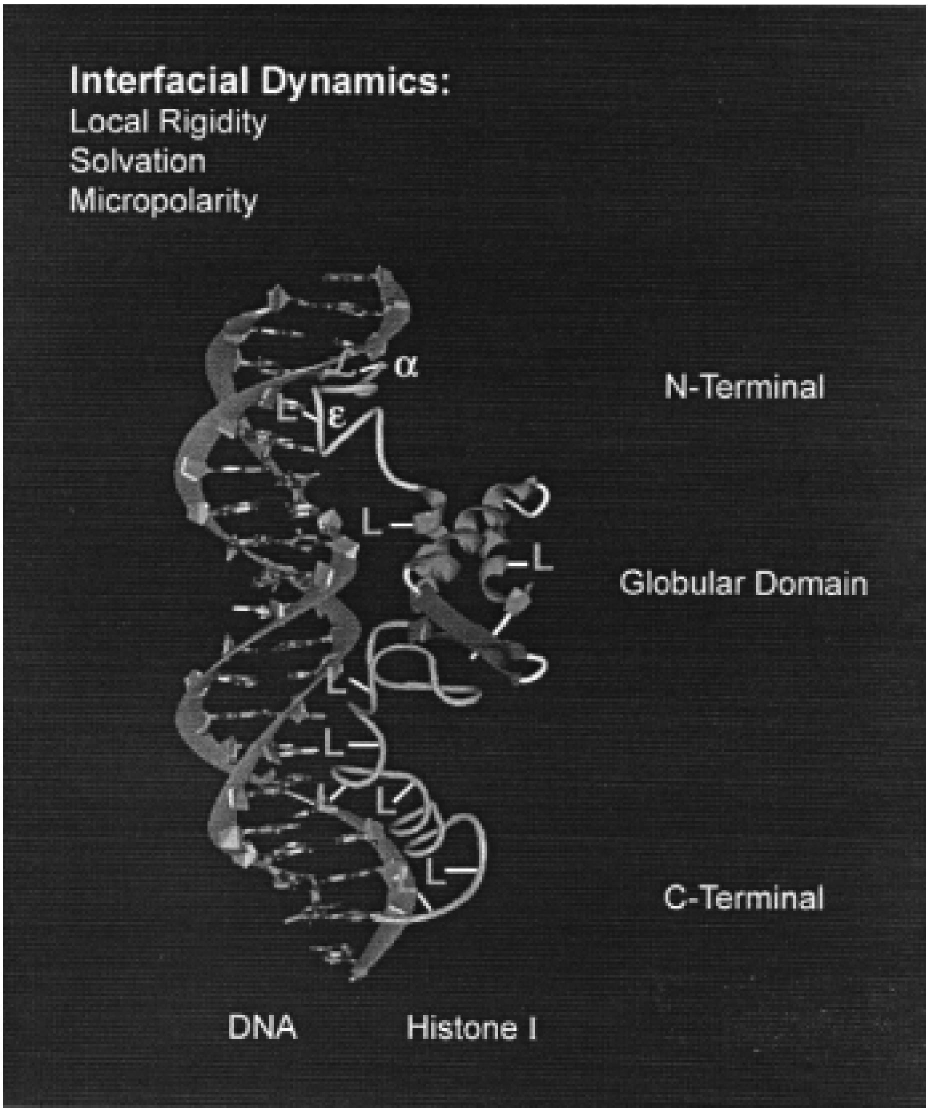
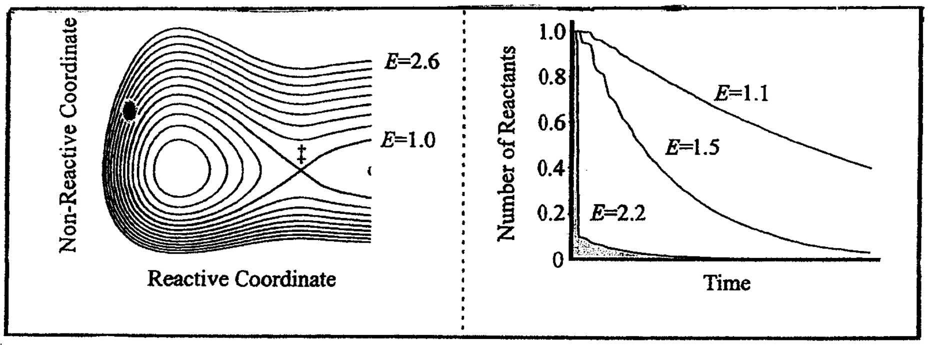


Figure 10. The protein (histone I)/DNA system studied in this laboratory, with the aim of elucidating the dynamics and the elements important in molecular recognition and chromatin condensation.



Møller and Zewail

Figure 11. Matter control with ultrashort laser pulses; suggestion made in the 1980 paper and the experimental demonstration and theoretical justification published nearly 20 years later.

was unknown. By controlling $\phi(t)$ we were able to make sequences of phase-coherent multiple pulses (optical analogue of NMR) and to tailor a composite "single" pulse with a prescribed $\phi(t)$. For example, with composite shaped-pulses, a sequence of phase segments and tilt angles (in the rotating frame) of, e.g., $60_x - 300_{\bar{x}} - 60_x$ we showed experimentally that the emission of a molecule can be made twice that as when a normal single pulse was used. Similarly, by choosing pulse sequences such as x-y-x($\bar{x}$) we experimentally locked the system and thus lengthened its relaxation time considerably.

On the fs time scale, we studied some elementary reactions, and recently, we turned our attention to complex molecular systems, but this time to implement the 1980 idea. In a series of molecules of increasing complexity, but retaining the same reaction coordinate, we studied selectivity control (IVR and entering near the transition state); the rate of reaction was two to three orders of magnitude larger than the expected *statistical* limit. This work was published in Science and promises to be significant for achieving non-statistical chemistry by localization at high energy, in time and space (see Figs. 4, 11). The concept suggests that control at high (chemical) energies is more realistic, in contrast with the conventional wisdom which asserts the need for low energies – time is of the essence! Further studies should explore other systems.

In the future, there will be extensions and new directions in fs light-matter control based on the temporal coherence of light and its interference with matter waves. Applications of the Tannor-Rice-Kosloff scheme will continue in this area of control on the fs time scale. One area that holds promise is the use of fs pulses to induce selectivity by utilizing the three parameters of the pulse, the central frequency, the width and the chirp, in an iterative algorithm; the chirp is, in a way, similar to a composite pulse of the type described above. The technique of liquid-crystal-display developed by Andy Weiner for fs pulse shaping, combined with the evolutionary feedback idea of Herschel Rabitz, makes possible the generation of the desired complex E(t) field to achieve (combinatorial) control. This optimal control has been demonstrated for a targeted second harmonic generation or a yield of chemical reaction as reported by Gustav Gerber's group in Würzburg.

Kent Wilson showed the importance of chirped pulses in focusing and reflecting wave packets and, in a more recent contribution, he, with Warren Warren, used the evolutionary feedback approach to optimize the fluorescence of a molecule in solution. It should be noted that all of the above schemes change the coherent composition of the initial packet and hence the evolution in different channels – but the evolution dictated by the natural forces of the atom remains unchanged! Intense fields may do so. We did not discuss here CW control schemes such as the one advanced by Paul Brumer and Moshe Shapiro.

VI. PERSPECTIVES

The key to the explosion of research can perhaps be traced to three pillars of the field.

(A) Time Resolution – Reaching the Transition-State Limit

Three points are relevant: (i) The improvement of nearly ten orders of magnitude in time resolution, from the 1950's (milli)microsecond time scale to present femtosecond resolution, opened the door to studies of new phenomena and to new discoveries; (ii) the cornerstone of reactivity, the transition state of structures in motion, could be clocked as a molecular species $TS^{\ddagger}$, providing a real foundation to the theoretical hypothesis for ephemeral species $[TS]^{\ddagger}$, and leading the way to numerous new studies. Extensions will be made to study transition state dynamics in complex systems, but the previous virtual status of the transition state has now given way to experimental reality; (iii) inferences deduced from "rotational periods" as clocks in molecular reactions can now be replaced by the actual clocking of the nuclear (vibrational) motion. In the 1960's, there was some thought that the relevant time scale for chemistry and biology was the microsecond (or longer) regime. Moreover, the uncertainty principle was thought to represent a severe limit of the utility of shorter time resolution; coherence was not part of the thinking in deciphering fs nuclear motion, as detailed above and summarized below.

(B) Atomic-Scale Resolution

Two points are relevant: (i) The transition from *kinetics* to *dynamics*. On the femtosecond time scale, one can see the coherent nuclear motion of atoms – *oscillatory* or *quantized steps* instead of *exponential decays* or rises. This was proved to be the case for bound, quasi-bound or unbound systems and in simple (diatomics) and in complex systems (proteins). (ii) the issue of *the uncertainty principle*. The thought was that the pulse was too short in time, thus broad in energy by the uncertainty principle $\Delta t \, \Delta E \sim \hbar$, but localization is consistent with the two uncertainty relationships and coherence is the key. The energy uncertainty ΔE should be compared with bond energies: ΔE is 0.7 kcal/mol for a 60 fs pulse. At the 1972 Welch Conference, in a lively exchange between Eugene Wigner and Edward Teller, even picosecond time resolution was of concern because of the perceived fundamental limitation imposed on time and energy by Heisenberg's uncertainty principle.

(C) Generality of the Approach

Three points are relevant: (i) In retrospect, the femtosecond time scale was just right for observing the "earliest dynamics" at the actual vibrational time scale of the chemical bond; (ii) the time resolution offers unique opportunities when compared with other methods. Processes often appear complex because we look at them on an extended time scale, during which many steps in the process are integrated; (iii) the methodology is versatile and general, as evidenced by the scope of applications in different phases and of different systems. It is worth noting that both *excited* and *ground state* reactions can be studied. It has been known for some time that the use of multiple pulses can populate the ground state of the system and, therefore, the population and coherence of the system can be monitored. The use of CARS, DFWM, SRS, π-pulses or the use of direct IR excitation are some of the approaches possible. Two recent examples demonstrate this point: one invokes the use of IR fs pulses to study reactions involving hydrogen (bond) motions in liquid water, work done in France and Germany; and the other utilizes CARS for the study of polymers in their ground state, as we did recently. Ground-state dynamics have also been studied by novel fs photodetachment of negative ions, and the subfield of fs dynamics of ions is now active in a number of laboratories.

VII. EPILOGUE

As the ability to explore shorter and shorter time scales has progressed from the millisecond to the present stage of widely exploited femtosecond capabilities, each step along the way has provided surprising discoveries, new understanding, and new mysteries. In their editorial on the tenth anniversary of femtochemistry, Will Castleman and Villy Sundström put this advance in a historical perspective. The recent Nobel report addresses with details the field and its position in over a century of developments (see Further Readings). Fig. 6 summarizes areas of study and the scope of applications in different phases and Fig. 8 highlights some advances in other areas, including medicine, nanotechnology, and metrology (see Further Reading). Developments will continue and new directions of research will be pursued. Surely, studies of transition states and their structures in chemistry and biology will remain active for exploration in new directions, from simple systems to complex enzymes and proteins, and from probing to controlling of matter.

Since the current femtosecond lasers (4.5 fs) are now providing the limit of time resolution for phenomena involving nuclear motion, one may ask: Is there another domain in which the race against time can continue to be pushed? Sub-fs or attosecond resolution may one day allow for the direct observation of the coherent motion of electrons. I made this point in a 1991 Faraday Discussion review and, since then, not much has been reported except for some progress in the generation of sub-fs pulses. In the coming decades, this may change and we may view electron rearrangement, say, in the benzene molecule, in real time, recalling, as in the femtosecond domain, “the uncertainty problem” is not a problem provided coherence of electron states is created.

Additionally, there will be studies involving the combination of the “three scales”, namely time, length and number. We should see extensions to studies of the femtosecond dynamics of *single molecules* and of *molecules on surfaces* (e.g. using STM). Combined time/length resolution will provide unique opportunities for making the important transition from molecular structures to dynamics and to functions. We may also see that all of femtochemistry can be done at micro-to-nano Kelvin temperatures, utilizing lasers and other cooling techniques.

It seems that on the femtosecond to attosecond time scale we are reaching the "inverse" of the big bang time, with the human heartbeat "enjoying" the geometric average of the two limits (Fig. 1). The language of molecular dynamics is even similar to that of cosmos dynamics. Cosmologists are speaking of energy landscapes and transition states for the big bang and universe inflation. Perhaps we are approaching a universal limit of time and matter!

FURTHER READING

Reports and Articles

(1) J.-M. Hopkins and W. Sibbett, "Ultrashort-Pulse Lasers", *Scientific American*, 283 (Sept. Issue), 73-79 (2000).

(2) A.H. Zewail, "Femtochemistry: Atomic-Scale Dynamics of the Chemical Bond using Ultrafast Lasers", in *Les Prix Nobel*, Stockholm, Sweden, pp. 110-203 (1999); *Angewandte Chemie*, Intern. Ed., 39, 2586-2631 (2000); German Ed., 112, 2688-2738 (2000)

(3) A.H. Zewail, "Laser Selective Chemistry – Is it Possible?", *Phys. Today* 33, 2-8 (1980).

(4) A.W. Castleman and V. Sundström (eds.), "Ten years of Femtochemistry: Time Resolution of Physical, Chemical and Biological Dynamics", *J. Phys. Chem. – Special Issue* (1998), pp. 4021-4404

(5) http://www.nobel.se/announcement-99.html

(6) B.M. Garraway and K.-A. Suominen, "Wave Packet Dynamics: New Physics and Chemistry in Femto-time", *Rep. Prog. Phys.* 58, 365-419 (1995).

Some Books

(1) V. Sundström (ed.), *Femtochemistry & Femtobiology*, World Scientific, Singapore (1997) [Nobel Symposium].

(2) P. Gaspard and I. Burghardt (eds.), *Chemical Reactions and Their Control on the Femtosecond Time Scale*, *Adv. Chem. Phys.* 101, Wiley, New York (1997) [Solvay Conference].

(3) A.H. Zewail, *World Scientific, Femtochemistry – Ultrafast Dynamics of the Chemical Bond*, Vols. I and II, New Jersey, Singapore (1994).

(4) E. Schreiber, *Femtosecond Real-Time Spectroscopy of Small Molecules & Clusters*, Springer, New York (1998).

(5) H.C. von Baeyer, *Taming the Atom*, *Random House*, New York (1992).

(6) P. Ball, *Designing the Molecular World*, Princeton Univ. Press, Princeton (1994).

THE NEW WORLD DIS-ORDER – CAN SCIENCE AID THE HAVE-NOTS?

AHMED H. ZEWAIL[1]

On our planet, every human being carries the same genetic material and the same four-letter genetic alphabet. Accordingly, there is no basic genetic superiority that is defined by race, ethnicity, or religion. We do not expect, based on genetics, that a human being of American or French origin should be superior to a human from Africa or Latin America. Moreover, it has been repeatedly proven that men and women from the so-called developing or underdeveloped countries can achieve at the highest level, usually in developed countries, when the appropriate atmosphere for excelling is made possible. Naturally, for any given population, there exists a distribution of abilities, capabilities and creativity.

In our world, the distribution of wealth is skewed, creating classes among populations and regions on the globe. Only 20% of the population enjoys the benefit of life in the "developed world", and the gap between the "haves" and "have-nots" continues to increase, threatening a stable and peaceful coexistence. According to the World Bank, out of the 6 billion people on Earth, 4.8 billion are living in developing countries; 3 billion live on less than $2 a day and 1.2 billion live on less than $1 a day, which defines the absolute poverty standard; 1.5 billion people do not have access to clean water, with health consequences of waterborne diseases, and about 2 billion people are still waiting to benefit from the power of the industrial revolution.

---

[1] Ahmed Zewail received the 1999 Nobel Prize in Chemistry and currently holds the Linus Pauling Chair at Caltech.

The per capita GDP[2] has reached, in some western, developed countries, $35,000, compared with about $1,000 per year in many developing countries and significantly less in underdeveloped populations. This factor of 40-100 times the difference in living standards will ultimately create dissatisfaction, violence and racial conflict. Evidence of such dissatisfaction already exists and we only have to look at the borders of developed-developing/underdeveloped countries (for example, in America and Europe) or at the borders between the rich and poor within a nation.

Some believe that the "new world order" and "globalization" are the solution to problems such as population explosion,[3] the economic gap and social disorder. This conclusion is questionable. Despite the hoped-for new world order between superpowers, the globe still experiences notable examples of conflict, violence and violations of human rights. The world order is strongly linked to political interest and national self-interest, and in the process many developing countries continue to suffer and their development is threatened. Globalization, in principle, is a hopeful ideal that aspires to help nations prosper and advance through participation in the world market. Unfortunately, globalization is better tailored to the prospects of the able and the strong, and, although of value to human competition and progress, it serves the fraction of the world's population that is able to exploit the market and the available resources.

Moreover, nations have to be ready to enter through the gate of globalization and such entry has requirements. Thomas Friedman, in his book "The Lexus and the Olive Tree", lists the following eight questions in trying to assess the economic power and potential of a country: "How wired is your country? How fast is your country? Is your country harvesting its knowledge? How much does your country weigh? Does your country dare to be open? How good is your country at making friends? Does your country's management 'get it'? and How good is your country's brand?" These

---

[2] Per capita gross domestic product (GDP) in U. S. dollars is the total unduplicated output of economic goods and services produced within a country as measured in monetary terms according to the U. N. System: Angola (528), Canada (19,439), China (777), Hong Kong (24,581), Egypt (1,211), Israel (17,041), North Korea (430), South Korea (6,956), Switzerland (35,910), U. S. A. (31,059), and Yemen (354). From U. N. Statistics Division.

[3] Overpopulation of the world, and its anticipated disasters, is not a new problem. It has been a concern for many millennia, from the time of the Babylonians and Egyptians to this day. Joel Cohen, in his book "How Many People Can the Earth Support?" provides a scholarly overview of the global population problem.

"eight habits of highly effective countries", according to Friedman, are the attributes countries need to succeed in the new era of globalization. The picture in mind is that countries are becoming like global companies, with the aim of being prosperous (in a timely manner). Organization and management and the technical know-how are essentials for a country to prosper; location, history, natural resources or even military might are no longer decisive!

Before attempting to address solutions, it is important to examine the origin of the problem by looking at the "anatomy of the gap". In my view, there are four forces which contribute to the barriers to achieving developed-world status:

Illiteracy: In many countries, especially those in the Southern Hemisphere, the illiteracy rate reaches 40-50% among the general population. Even worse, in some countries, the illiteracy rate among women is above 70%. These rates reflect the failure of educational systems, and are linked to the alarming increase in unemployment. One cannot expect to seriously participate in the world market with this state of unpreparedness. In the west, illiteracy on this scale has been essentially eliminated, and nowadays often means a lack of expertise with computers, not the inability to read and write! Of course, some now developed countries had high illiteracy rates when they began their development, but we must recall that scientific know-how was possessed by a significant portion of the population.

Incoherent Policy for Science & Technology: The lack of a solid science & technology base in the world of have-nots is not always due to poor capital or human resources. Instead, in many cases, it is due to a lack of appreciation for the critical role of science & technology, an incoherent methodology for establishing a science & technology base, and an absence of a coherent policy addressing national needs, human and capital resources (even in some developed countries, we are witnessing the consequences of the latter). Some countries believe that science and technology are only for rich nations. Others consider scientific progress to be a luxury, not a basic need, that it is only necessary to pursue after the country has solved other demanding problems. Some rich, but developing, countries believe that the base for science and technology can be built through purchases of technology from developed countries. These beliefs translate into poor, or at most, modest advances and in almost all cases the success is based on individuals, not institutional teamwork. These complex problems are made worse by the fact that there are many slogans, reports and showcase efforts which do not address the real issues and are intended for local consumption.

Restrictions on Human Thought: Real progress requires the participation of knowledgeable people working together to address key problems and possible solutions. In the west, this participation involves senior and junior people and their different areas of expertise in exchanges of human thought and knowledge. The result is a planned recommendation, designed to help different sectors of the society. In many developing countries, although this practice is true on paper, it is usually not followed in reality. The reasons are many, including hierarchical dominance, strong seniority systems and the centralization of power; all limit people's ability to speak freely. Although western democracies are not the only successful models for government, a lack of democratic participation suppresses collective human thought and limits "due process of the law", which unfairly stifles human potential.

Fanatical Mix-ups of State Laws and Religious Beliefs: Confusion and chaos result from the misuse of the fundamental message of religion, namely the ethical, moral and humanistic ingredients in the life of many, a significant fraction of world population. For example, in Islam the message is clear, fully expressed in the Holy Quran to Muslims, who are close to one billion in global population. The Quran makes fundamental statements about human existence and integrity, on everything from science and knowledge to birth and death. "READ" is the first word in the first verse of the direct Revelation to The Prophet [Sura Alaq 96:1] and there are numerous verses regarding the importance of knowledge, science and learning; Muslims position scientists along with the prophets in the respect they are due. The Quran also emphasizes the critical role that humans must play in the struggle to achieve and develop, stating, *"Verily! Allah will not change the good condition of the people as long as they do not change their state of goodness themselves."* [Sura Al Ra'd 13:11]. All societies and religions experience some fanaticism, but the current disparity in the world economy, with the dominance of the west, and the new role of invading media and politics trigger real fear for the possible loss of religious and cultural values. This situation, with increased unemployment, results in rigidity towards progress and the release of frustration in different ways. The west is seen by many as responsible for some of the mix-up, first because there is inconsistency in political actions by the west, and second because of the gap between the rich and the poor; between billionaires and the homeless.

What is needed to solve these problems? The answer to this question is non-trivial because of the many cultural and political considerations that are part of the total picture. Nevertheless, I believe that the four issues identified above point to the essentials for progress, which are summarized in the following: *(1) Building the human resources*, taking into account the necessary elimination of illiteracy, the active participation of women in society, and the need for a reformation of education: *(2) Rethinking the national constitution*, which must allow for freedom of thought, minimization of bureaucracy, development of a merit system, and a credible (enforceable) legal code; *(3) Building the Science Base*. This last essential of progress is critical to development and to globalization and it is important to examine this point further.

There is a trilogy which represents the heart of any healthy scientific structure: *First, the Science Base*. The backbone of the science base is the investment in the special education among the gifted, the existence of centers of excellence for scientists to blossom, and the opportunity for using the knowledge to impact the industrial and economical markets of the country and hopefully the world. In order to optimize the impact, this plan must go hand-in-hand with that for the general education at state schools and universities. This base must exist, even in a minimal way, to ensure a proper and ethical way of conducting research in a culture of science which demands cooperation as a *team effort* and as a search for the truth. The acquisition of confidence and pride in intellectual successes will lead to a more literate society. *Second, the Development of Technology*. The science base forms the foundation for the development of technologies on both the national and international level. Using the scientific approach, a country will be able to address its needs and channel its resources into success in technologies that are important to, for example, food production, health, management, information, and, hopefully, participation in the world market. *Third, the Science Culture*. Developing countries possess rich cultures of their own in literature, entertainment, sports and history. But, many do not have a “science culture”. The science culture enhances a country’s ability to follow and discuss complex problems rationally, and based on facts, while involving many voices in an organized, collective manner – scientific thinking becomes essential to the fabric of the society. Because science is not as visible as entertainment, the knowledge of what is new, from modern developments in nutrition to emerging possibilities in the world market, becomes marginalized. With a stronger scientific base, it is possible to enhance the science culture, foster a rational approach, and educate the public about potential developments and benefits.

The above trilogy represents a major obstacle to the have-nots, as many feel that such a structure is only for those countries which are already developed. Some even believe in conspiracy theories – that the developed world will not help developing countries and that they try to control the flow of knowledge. The former is a chicken/egg argument because developed countries were developing before they achieved their current status. The recent examples for success in the world market in countries such as developing China and India and others are because of the developed educational system and technological skills in certain sectors – India is becoming one of the world leaders in software technology and "Made in China" goods are now all over the globe. As for the conspiracy theory, I personally do not give significant weight to it, preferring to believe that nations "interact" in the best of their mutual interests. If the gap is too large, the interest becomes marginalized, but if the gap narrows, the flow of information (including science and technology) becomes easier, even if the two nations involved "do not really have an affinity to each other."

What is needed is acceptance of responsibility in a collaboration between developing and developed countries. I see two sets of responsibilities in what I term a "proposal for partnership". The proposal highlights the following three points for each of them.

Responsibilities of Developing Countries:

(1) Restructuring Education and Science. The force of expatriates in developed countries should be organized and used for help in a serious manner. Expatriates can help the exchange between developed-developing cultures and assist in bringing modern methods of education and research. This will not be successful without the genuine participation of local experts.

(2) Creation of Centers of Excellence. These centers should be limited to a few areas in order to build confidence and recognition and should not be just exercises in public relations. They are important not only for research and development, but also in preparing a new population of experts in advancing technologies. They would also help reduce the brain drain many developing countries experience.

(3) Commitment of National Resources. These resources are needed to support research and development in a selective way, following well-established criteria that are based on merit and distinction. To guide national policy, government at the highest level should create an overseeing "Board for Science & Technology", formed from national and international experts. Without serious commitment to such an effort, progress will remain limited.

Some developing countries have made admirable progress in these areas, and the results from, e.g., India, South Korea, and Taiwan reflect healthy educational reforms and excellence in some science and technology sectors. In Egypt, the University of Science and Technology (UST) is an experiment, initiated with the hope of establishing a center of excellence that will satisfy the criteria of the above trilogy: nurturing the science base, developing technologies important to the region and the world, and fostering the science culture. So far we have had success in structuring an academic foundation and, with the commitment of President M. Hosni Mubarak, we now have a 300-acre parcel available to build a campus on the outskirts of Cairo. We are awaiting the approval of a new law which will position UST as a non-profit, non-governmental organization. This will be a unique experiment where both developing and developed countries can participate, helping a region rich in human capital and potential but in need of peace and prosperity. By the time UST reaches its final stage, it should have satellites benefiting other countries in the area.

Responsibilities of Developed Countries:

(1) Focusing of Aid Programs. Usually an aid package from developed to developing countries is distributed among many projects. Although some of these projects are badly needed, the number of projects involved and the lack of follow-up (not to mention some corruption) means that the aid does not result in big successes. More direct involvement and focus are needed, especially to help Centers of Excellence achieve their mission, and with criteria already established in developed countries.

(2) Minimization of Politics in Aid. The use of an aid program to help specific regimes or groups in the developing world is a big mistake, as history has shown that it is in the best interests of the developed world to help *the people* of developing countries. Accordingly, an aid program should be visionary in addressing real problems and should provide for long-term investment in the development program.

(3) Partnership in Success. There are two ways to aid developing countries. Developed nations can either give money that simply maintains the economic and political stability or they can become a partner and provide expertise and a follow-up plan. This serious involvement would be of great help in achieving success in many different sectors. I believe that real success *can* be achieved provided there exists a sincere desire and serious commitment to a partnership, which is in the best interests of both parties.

What is the return to rich countries for helping poor countries? And what payoff do rich countries get for helping poor countries get richer? These two questions were asked by Joel Cohen in his book mentioned before. At the level of a human individual, there are religious and philosophical reasons which make the rich give to the poor – morality and self-protection motivate us to help humankind. For countries, mutual aid provides (besides the issue of morality): insurance for peaceful coexistence and cooperation for preservation of the globe. If we believe that the world is becoming a village because of information technology, then in a village we must provide social security for the unprivileged, otherwise we may trigger revolution. If the population is not in harmony, grievances will be felt throughout the village and in different ways.

Healthy and sustainable human life requires the participation of all members of the globe. Ozone depletion, for example, is a problem that the developed world cannot handle alone – the use of propellants with chlorofluorocarbons (CFCs) is not only by the haves. Transmission of diseases, global resources, and the Greenhouse Effect are global issues and both the haves and have-nots must address solutions and consequences. Finally, there is the growing world economy. The market (and resources) of developing countries is a source of wealth to developed countries and it is wise to cultivate a harmonious relationship for mutual aid and mutual economic growth. I heard of a recent phrase, “Give us the technology and we will give you the market!”, used to describe the US-China relationship.

A powerful example of visionary aid is the Marshall Plan given by the United States to Europe after World War II. Recognizing the mistake made in Europe after W.W.I, the U. S. decided in 1947 to help rebuild the damaged infrastructure and to become a partner in the economical (and political) developments. Western Europe is stable today and continues to prosper – likewise its major trading partner, the United States of America. The U. S. spent close to 2% of its GNP on the Marshall Plan for the years 1948-51. As pointed out by Cohen, a similar percentage of the $6.6 trillion of the 1994 U. S. GNP will amount to $130 billion, almost ten times the $15 billion a year currently spent for all non-military foreign aid and more than 280 times the $352 million the U. S. gave for all overseas population programs in 1991. The commitment and generosity of the Marshall Plan resulted in a spectacular success story. The world needs a rational commitment to aid and aid partnerships.

It is in the best interest of the developed world to help developing countries become self-sufficient and a part of the new world order and market.

Some developed countries are recognizing the importance of partnership, especially with neighbors, and attempts are made to create new ways of support and exchanges for the know-how. Examples include the United States and Mexico and Western and Eastern Europe. The rise of Spain's economic status is in part due to the partnership within Western Europe.

In the next 25 years, 2 billion human beings will be added to the planet, with 97% of those 2 billion people living in the developing world. This uneven population explosion, with its impact on world resources, the environment and regional conflicts, threatens our existence and calls for serious and active involvement. The consequence when developing countries acquire an "underdeveloped status" is ugly, not only because of the human costs and sufferings, but also because of the impact on world peace and stability. It is equally in the best interests of developing countries to address these issues seriously, not through slogans, but with a commitment of both will and resources in order to achieve real progress and to take a place on the map of the developed world.

We may picture the current situation by likening it to a "Ship in a Flood". Underdeveloped countries are near to sinking under the deluge; developing countries are trying to make it onto the ship; and developed countries sailing, *but* in a flood of the unprivileged. The choices are clear: The sailing ship must seriously attempt to help those who are trying to make it. Those trying to make it should not regard the ship without a willingness to put forth their own effort, and without wasting their energy on conspiracy theories – being on the ship is more important! Meanwhile, everyone must make every attempt to rescue those at the bottom. To be part of a civilized planet, every human must matter. The notion of "us" and "them" is not visionary and we must speak of global problems and solutions. At the heart are poverty, illiteracy, and human freedom.

WHY AND HOW PHYSICISTS ARE INTERESTED IN THE BRAIN AND THE MIND

MINORU ODA

Hitherto, brain research has been carried out with pathological, physiological and psychological approaches. Apart from the experts in neuroscience, scientists in general are now more interested in brain research, as I have emphasised here in this Academy on some occasions in the past [1, 2]. And meetings by physicists have been held.

Ever since Masao Itoh founded a Brain Research Institute in the RIKEN Institute, Japan, and gathered together there a group of (experimental and theoretical) neuroscientists, as well as scientists from a variety of disciplines, more and more physicists have become interested in the brains of humans, small animals such as cats, dogs, apes, fish, and insects such as bees and ants.

Three approaches adopted by physicists may be delineated:

1) understanding the brain as though it were a computer;

2) producing new concepts where the computer is seen as an imitator of the brain;

3) observing physical traces left on the brain caused by the activities of the brain.

If, as suggested, the traces left in the brain are observable more or less randomly and can be freely detected, then the relevant issues may be listed as follows:

The brain of the foetus: when and how does the brain of human and animal foetuses grow to be brain-like in the mother's body? What is the physical mechanism involved?

What should be said about the imprinting of the brains of chicks as discovered by K. Lorenz?

When we or animals sleep what happens to our brains?

How do tropical fish control their ‘millisecond’ reaction of motion?

How do the brains of adult salmon or baby eels recognise their original mother-river so that they can return to it after their long journeys in the ocean?

What controls the swift group motion of birds and fish?

The visual cognition of stellar constellations (?) as opposed to traces in the brains of migrating birds (if they exist)?

The question of auditory cognition versus traces in the brain: noisy and musical sounds; group singing (e. g. cricks, sparrows). How do the brains of spring-singing birds evolve into those of autumn-singing birds?

The human brain: are there any differences in the brain which underlie Western or Eastern languages?

The brains of musicians: how do the brains of pianists, violinists, and conductors work differently?

How do the brains of painters work? When the drawing is started and when the painting is about to be finished.

The social behaviour of groups of animals, birds, fish, and insects can be watched and followed by means of telemetry.

The relationship which exists between instincts and evolution: how does a group of animals or insects develop or acquire and fix its instinct? How do insects such as bees or ants acquire differentiation as regards soldiers, workers, and the queen? How are instincts developed and fixed?

The Observation of the Brain

Now, what could be the techniques to look into traces in the brain which have a high spatial resolution? The X-ray astronomy technique, which we may call the Fourier Transform Telescope (FTT), can be converted.

The principle of the FTT, which was conceived as a high angular-resolution telescope for the angular resolution of arc-seconds for X-ray imaging, may be understood with reference to Fig. 1. The metal grid structure shown in Fig. 2 (see p. XIII) is attached to a solid structure and fixed with a certain relative distance. Combination of the grid units with a certain spatial frequency and a unit of the same frequency, a quarter phase displaced, and with a certain angular orientation with the corresponding grid, can produce a point on the Fourier u-v plane as shown in Fig. 3. The configuration of the points on the u-v plane produces an image. The principle of the FTT can be converted to that of the Fourier Transform Microscope (FTM) to achieve high-resolution images of the traces in the brain.

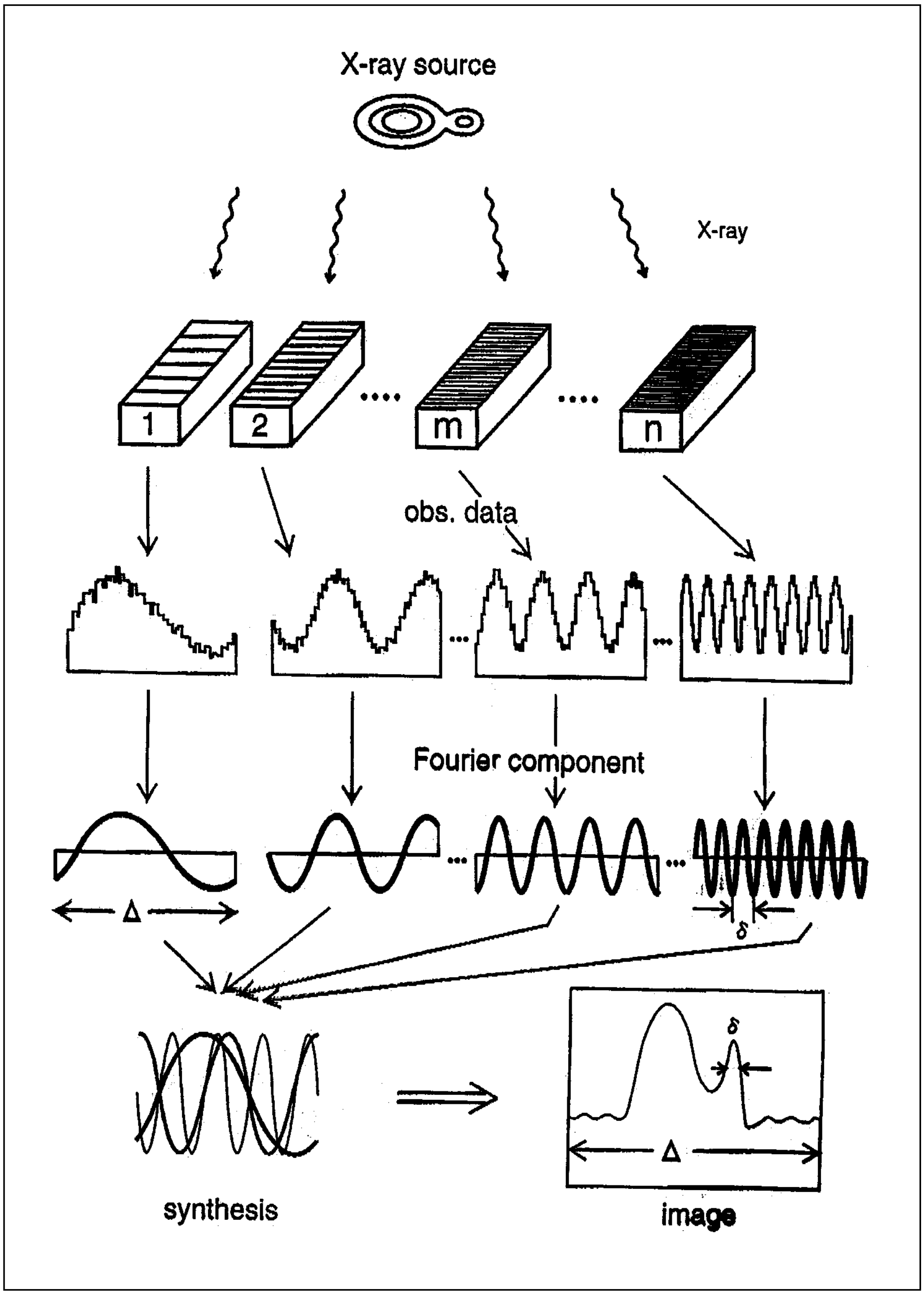
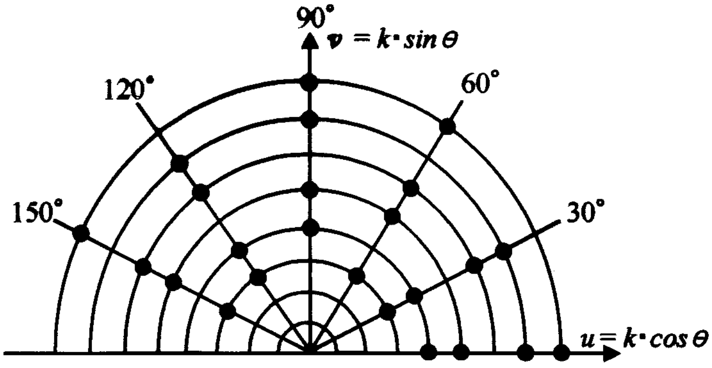

X-ray source
X-ray
1
2
m
n
obs. data
Fourier component
Δ
δ
synthesis
δ
Δ
image

Fig. 1



Fourier $u - v$ plane for the FTT

Fig. 3

Among the variety of ways by which to produce X-ray sources in the brain, Fig. 4 (see p. XIII) illustrates how a minus muon beam produced by a facility of the RIKEN/Rutherford Appleton Laboratory can irradiate targets in the brain and produce muonic atoms which in turn produce LX-rays.

Thus, images of metal concentrations in the brain, which are normally physiological or pathological, can be produced. The combination of grids at the distances corresponds to the point on the Fourier u-v plane by which the image can be reproduced with a high spatial resolution.

Group Evolution to Instinct

The relationships within social evolution as described by the late Dr. Motoo Kimura and by Freeman Dyson, and the development and fixing of the instinct of the group, can be experimentally understood in the case of the differentiation of soldiers, workers, and queens in the case of insects, such as bees or ants.

Such experiments on the relationship between evolution and the acquisition of instinct by insects can be attempted using the combination of techniques of FTM, telemetry, and the technique of the freezing and defrosting after some length of time of eggs and sperm, as developed in a laboratory of the RIKEN, the Yokohama Institute.

Brain science as seen from the viewpoint of experimental physicists has in this paper thus been described and discussed.

REFERENCES

[1] *Proc. Japan Acad.*, 71 (1995), pp. 1-4.
[2] A memo on this subject was circulated during the Meeting of October 1998.

A MILLENNIUM VIEW OF THE UNIVERSE

VERA C. RUBIN

We live in a universe that is amazingly beautiful, enormously large, and incredibly complex. Only during the 20th century have we had the tools and the technology to discover some of its secrets. Progress in understanding the universe has been one of the major intellectual achievements of this century. Yet our understanding is far from complete. I believe that there are deep mysteries that we have yet to uncover.

Due principally to the work of Kapteyn, De Sittter, Oort, Einstein, Lemaître, Hubble, Shapley, and others, 70 years ago we learned that we live in a Galaxy, that the universe is populated with billions of other galaxies, and that galaxies are moving away from each other. The best explanation is that the universe originated in an enormously hot, dense singularity, and has been expanding and cooling ever since. As the universe evolves, galaxies evolve, stars evolve, planets evolve, and life evolves. Only recently have we understood how interrelated are all the features of the universe. Almost a century ago, John Muir (1915) wrote, “When we try to pick out anything by itself, we find it hitched to everything else in the universe”. It is these connections that I would like to identify today.

From observations of the nearby universe, we have learned:

(1) The universe is lumpy; stars form into galaxies, galaxies join into clusters, and clusters merge into superclusters.

(2) Gravity is the dominant force. Over large regions of space, whole streams of galaxies are being pulled toward regions of higher density.

(3) Most of the matter in the universe is dark. At least 90%, perhaps as much as 99%, has never been observed directly. Some of it may be conventional matter that is too faint to detect or for which radiation is not one of its properties. Some of it may be unconventional matter of a form predicted by some theories. It could be something we have not yet imagined.

(4) Almost all research questions that we have asked have yet to be finally answered. We do not know the age of the universe, the ages of the oldest stars, the density of the universe, how life originated on Earth, how soon galaxies originated following the big bang, and the ultimate fate of the universe. We do not know what the dark matter is.

These are the questions that will be answered in the future.

Let me start with a description of what we can see and what we know, by describing the geography of the universe around us. When you look at the sky on a dark night from the northern hemisphere, every star that you see is a member of our own spiral Galaxy. That means the stars are gravitationally bound, all orbiting in concert about the very distant center of our Galaxy. The stars are not distributed at random, but are flattened to a plane. The sun, our star, is located in the plane. And when we look through the plane we see on the sky a band of millions of stars, which we call the Milky Way.

Most ancient civilizations told stories to explain the Milky Way. It was not until 1609 that Galileo turned his newly perfected telescope to the sky and discovered that the Milky Way was composed of “congeries of stars”. I like to say that Galileo advanced science when he took a cardboard tube, and placed a small lens at one end and a large brain at the other. Galileo’s great genius was not only that he discovered things never before seen in the sky, but that he was able to understand and interpret what he saw.

Our Galaxy contains more than just stars. It contains clouds of gas and dust which may obscure more distant objects. From our position in the Galaxy we cannot see all the way to its center. When we use the telescope to look away from the plane of our Galaxy, we see external galaxies, each an independent agglomeration of billions of stars. In each galaxy, all the stars are gravitationally bound to that galaxy. Telescopic views of external galaxies convince us that we understand the structure of our Milky Way.

For the purposes of what I am going to be discussing today, there are two major facts to remember. In a galaxy, stars are very, very far apart. Relative to their diameters, the average distance between one star and the next is enormous. That is not true for galaxies. Virtually every galaxy has a companion galaxy within a few diameters. The second fact is that gravity is the force that controls stellar motions. Gravity is also the dominant force in the evolution of galaxies.

Figure 1 (see p. XIV) is a near-infrared photograph of the center and about 90 degrees on either side of the disk of our Galaxy. It was made by the orbiting COBE Satellite. This is the best picture I know of our Galaxy, and this is the photograph that should hang in schoolrooms around the world. Just as students should know about continents and oceans and polar caps and volcanoes, so they should also know about galaxies and the structure of the universe.

Seen face on, our Galaxy would look like the wide open spirals (Figure 2; see p. XIV) that we photograph with our telescopes; our sun is located far from the nucleus on the edge of a spiral arm. The sun, carrying the planets with it, has an orbit which carries it once around the galaxy in two hundred million years. Hence the sun has orbited about 20 or 30 times around the Galaxy since its formation.

The spiral arms of a galaxy are not fixed loci of stars, but regions in which the stellar density is high. A star will move into an arm and out of an arm, spending a longer period in the arm because of the higher gravity there. A fair analogy is a traffic jam on a road. If you look at a road where there is a bottleneck you will always see cars there, but from one time to the next they will not be the same cars.

As the universe cooled following the hot big bang, atoms of hydrogen and helium eventually formed, and from these elements the first generation of stars was made. It takes two things to form a star: gas, and gravity sufficient to cause the gas to contract to high density. As more gas particles are gravitationally attracted to the increasingly massive protostar, their infall energy is transformed to heat, raising the central temperature. Ultimately, the central temperature will be high enough that the star will start fusing atoms of hydrogen into helium, and helium atoms into heavier elements. During its lifetime, a star is a chemical factory for making elements more complex than the elements from which it formed. As it forms elements up to iron, energy is released, producing the starlight to which our eyes are sensitive. It is not a coincidence that human eyes have their peak sensitivity in the region of the spectrum which matches the peak of the visible solar radiation.

Ultimately, the star reaches an energy crisis, for it takes energy to produce chemical elements heavier than iron. The star reaches the end of its life, either gently, by shedding its outer atmosphere (Figure 3; see p. XV) or explosively by becoming a supernova (Figure 4). In either case, the star enriches the gas between the stars with heavier elements; these are the building blocks of future generations of stars. In some cases, it is the shock wave from the exploding supernova that compresses nearby gas, thus initiating a new generation of star formation. These stars are composed of atoms including carbon and nitrogen and oxygen, the elements necessary for life.

Star formation is a messy process, and the forming star is left with a residual disk of debris particles. Planets will ultimately form in this disk

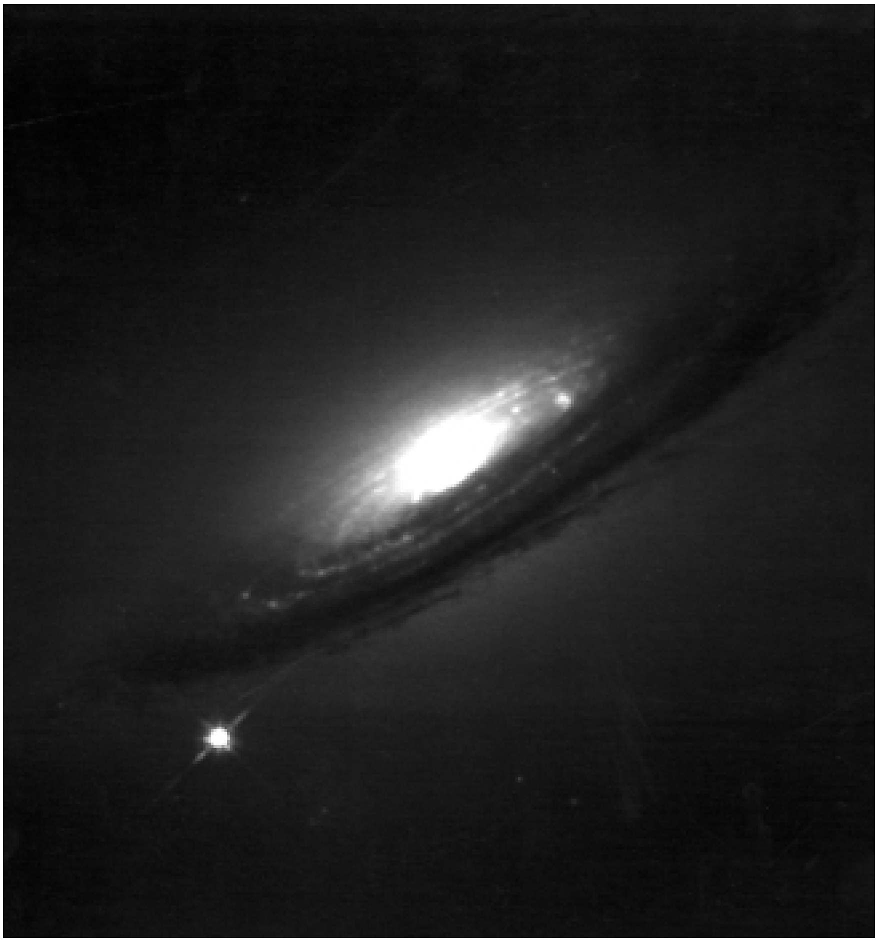


Figure 4. An image of NGC 4526, a galaxy in the Virgo cluster, taken with the Hubble orbiting telescope. The bright star is a supernova in that galaxy, SN 1994D. Credit: V.Rubin, STScI, and NASA.

from the merging of dust particles. From these particles will emerge the Earth with its iron core and its floating continents, and its biology and its living creatures. Without our Galaxy to gravitationally retain the gas atoms and molecules, without stars to make the heavy elements, and without the debris from our forming sun, the Earth and its living forms would not exist. John Muir would have liked to know this story.

Our Galaxy is not alone in space. We have two small nearby satellite galaxies, the Magellanic Clouds, visible in the sky with the naked eye from the southern hemisphere. The Magellanic Clouds orbit our Galaxy, and each orbit carries them through the gas layer of our disk. The gas between the stars is tidally disrupted as the Clouds move through. The Clouds lose energy, and their orbits diminish. Ultimately the Magellanic Clouds will cease to exist as separate galaxies. Instead, they will merge and become part of our Galaxy. A tidal tail of gas, pulled out of the Magellanic Clouds on a previous passage, is observed today by radio telescopes as a large arc of gas across the sky. The Sagittarius Dwarf, an even closer galaxy located beyond the nucleus on the other side of our Galaxy, is currently being pulled apart. Such smaller galaxies are gravitationally fragile, and hence at risk of capture by nearby, more massive galaxies.

Our Galaxy has another relatively close, but very large, companion, the Andromeda galaxy (M31). This nearest large galaxy to us has long been a favorite for study. M31 also has two bright satellite galaxies, and many fainter ones. The Andromeda galaxy and our own Galaxy are dominant members of the Local Group of galaxies. The Local Group consists of about twenty known galaxies, only a few of them large. Most are small irregular objects, each lacking a massive center. Hence they are gravitationally very fragile when they pass near larger galaxies. Ultimately, they will probably each merge with the more massive galaxy. The halo of our Galaxy contains sets of stars which were probably acquired in this fashion.

We live in an age when clusters of galaxies are forming. In some regions of space, the mutual gravity of the galaxies has overcome the expansion of the universe, and numerous galaxies gravitationally clump into one large system. Our Local Group is an outlying member of the Virgo Supercluster. Like clusters and superclusters, the Virgo Cluster contains many spheroidal galaxies. Many of these spheroidal galaxies probably formed from the merger of two or more disk galaxies, an occurrence expected frequently in the high galaxy density core of a cluster of galaxies. Spheroidal galaxies are a favorite laboratory for studying stellar motions.

This is the lumpy structure of the nearby universe is emphasized in Figure 5. We live in a spiral Galaxy that has one major companion in the Local Group. This group of galaxies is an outlying member of a large supercluster of thousands of galaxies centered on the Virgo Cluster. The gravitational attraction of the Virgo Cluster on our Galaxy is slowing down our expansion. We are expanding from Virgo due to the expansion of the universe, but at a lower speed than we would have if the Virgo galaxies were

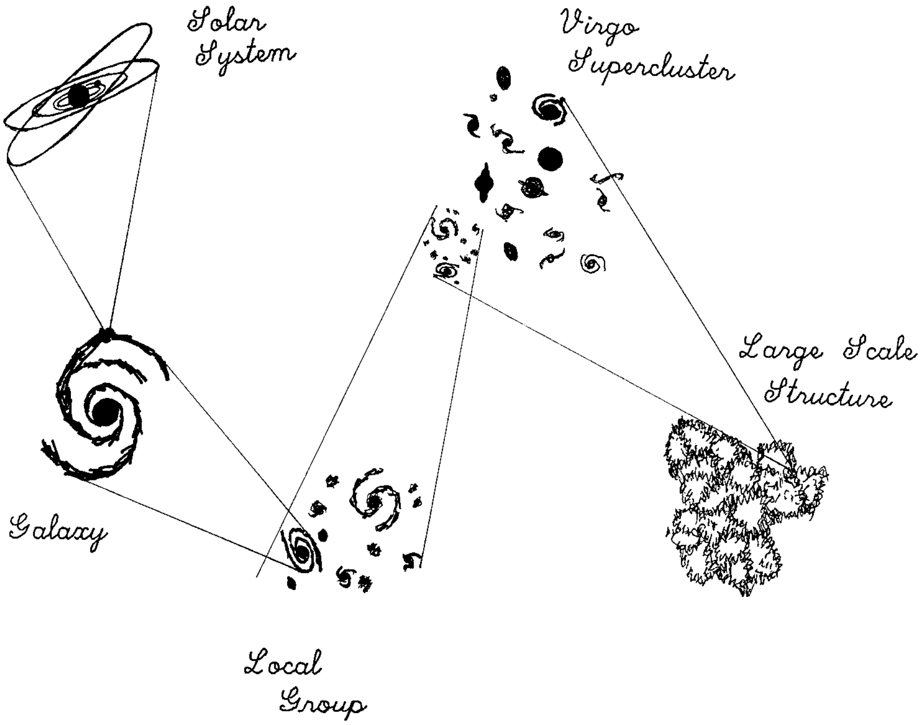


Figure 5. A sketch of the observed luminous universe, emphasizing the lumpy structure. We live on a planet orbiting a star; the star is located on the edge of a spiral arm of our Milky Way Galaxy, which is one galaxy in the Local Group of galaxies. The Local Group is an outlying member of the Virgo Supercluster, which forms one of the knots in the lumpy universe.

not there. At the center of the Virgo Cluster, the local gravitational field is so great that the expansion of the universe has been halted. The core of the cluster is not expanding, for the galaxies are all gravitationally bound to each other.

When we map the distribution of the bright galaxies on the sky, we find that their distribution is not uniform and not random. Instead, the galaxies are distributed in clusters, and the clusters form superclusters. There are galaxies in lace-like chains connecting the superclusters, as well as large regions in which no galaxies are seen. We do not know if these dark regions are void of all matter, or only void of bright matter.

I now want to turn to the evidence that there is very much dark matter in the universe. For many years I had been interested in the outer boundaries of galaxies, a subject relatively far from the mainstream of astronomy. I devised an observing program to take advantage of the new large telescopes, which would permit us to discover how stars in the outer disk orbit their galaxy center. Most of the observations were made at the Kitt Peak National Observatory outside of Tucson; others come from the Cerro Tololo Inter-American Observatory, and the cap. O of the Carnegie Institution of Washington in Chile.

By analogy with planets in the solar system, it was assumed that stars far from the galaxy center would orbit with velocities much slower than those near the galaxy center. Since before the time of Isaac Newton, scientists knew the orbital periods of the planets, Mercury, Venus, Earth, Mars, Jupiter, and Saturn, and their distances from the sun. The planet closest to the sun, Mercury, orbits very rapidly while Saturn, the planet distant from the sun, orbits very slowly. Newton taught us that gravitational forces fall off as the square of the distance from the sun, the source of the gravitational attraction in the solar system. And the planets, as all physics students know, are actually falling to the sun, but their forward motion is so great that they never reach the sun, but instead they describe an orbit. From their distances from the sun and their orbital periods, we can deduce the mass of the sun.

By similar reasoning, the mass within a galaxy can be determined from the orbital velocities of stars or gas at successive distances within that galaxy, until we reach the limit of the optical galaxy. My colleague Kent Ford and I would use at a telescope a spectrograph that splits the light from a galaxy into its component colors. Hydrogen atoms within the stars and gas produce spectral lines whose positions vary with the velocity of the source. Lines are shifted to the red for a source moving away from an observer, and shifted to the blue for sources moving toward the observer. The long slit of the spectrograph accepts light from each point along the major axis of that galaxy (Figure 6). The rotation of the galaxy carries the stars toward us on one side (therefore blue shifted), and away from us on the other side (red shifted).

By measuring the positions of the lines with great accuracy, I deduce the velocity for each observed position in the galaxy. I have obtained hundreds of spectra of galaxies, which I then study at my office. Now I record the observations and carry them via computer rather than photographic plates. In virtually all cases, the orbital velocities of stars far from the nucle-

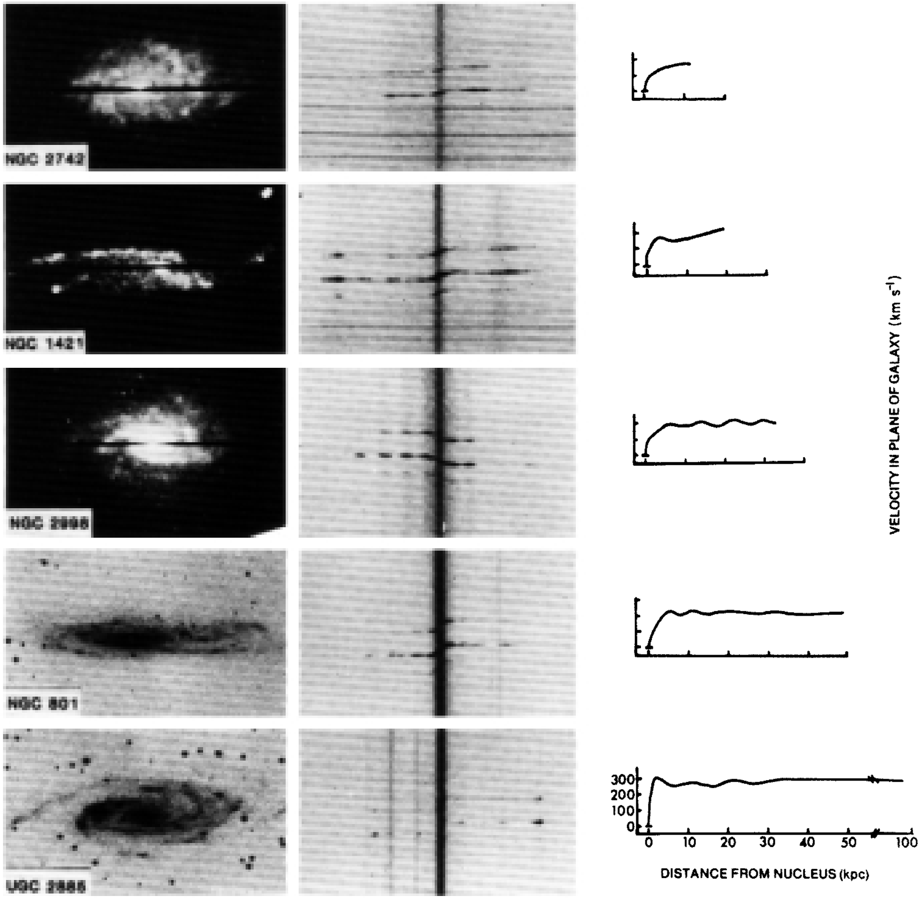


Figure 6. Images, spectra, and rotation velocities for 5 spiral galaxies. The dark line crossing the upper three galaxies is the slit of the spectrograph. The spectra show emission lines of hydrogen and nitrogen. The strongest step-shaped lines in each are from hydrogen and ionized nitrogen in the galaxy. The strong vertical line in each spectrum comes from stars in the nucleus. The undistorted horizontal lines are from the Earth's atmosphere. The curves at right show the rotation velocities as a function of nuclear distance, measured from emission lines in the spectra.

us are as high or even higher than orbital velocities of stars closer to the bright galaxy center.

Figure 6 shows five galaxies, their spectra, and their measured velocities. Whether the galaxies are intrinsically small, or intrinsically large, the rotation velocities remain high far from the nucleus. If you are a first year physics student, you know that in a system in equilibrium, a test particle orbiting a central mass M at a distance R moves with velocity V, such that the M is proportional to R times V (squared). The mass of the test particle does not enter. Thus the velocity of a gas cloud or a star (or any other test object) does not enter into the equation. This is what Galileo was trying to show when he dropped objects from the Tower of Pisa. It is not the mass of the falling (or orbiting) object which determines its velocity; it is the mass of the attractor, be it Earth or a galaxy.

As we see in Figure 6, orbital velocities are almost constant independent of distance. These tell us that the mass detected within the galaxy continues to rise with increasing distance from the center of the galaxy. Although the light in a galaxy is concentrated toward the center, the mass is less steeply concentrated. We do not know the total mass of a single galaxy; we know only the mass interior to the last measured velocity.

These high rotational velocities far out in a galaxy are one piece of evidence that most of the matter in a galaxy is dark, and that the dark matter extends beyond the optical galaxy. Stellar velocities remain high in response to the gravitational attraction of this extended distribution of dark matter. Some galaxies have hydrogen disks that extend well beyond the optical galaxy. Observations of velocities in these extended disks reveal that the rotation velocities remain high across the disks. The hydrogen gas is not the dark matter, but it too responds to the gravitational attraction of the extended dark matter. Astronomers call the distribution of dark matter a halo, but actually mean a spheroidal distribution in which the galaxy disk is embedded.

Questions concerning the dark matter remain; astronomers and physicists cannot yet supply the answers. Does it exist? Where is it? How much is there? What is it? I will briefly give the current thinking on each of these, from the view of an observer.

Does it exist? Most astronomers believe that it does. There are only two explanations that can explain these unexpectedly high orbital velocities in spiral galaxies. One possibility is that Newtonian gravitation theory does not apply over distances as great as galaxy disks, for this theory underlies our analysis. There are physicists who are attempting to devise cosmological models in which Newtonian gravitational theory is modified. But, if you accept Newton’s laws, as most astronomers do at present, then the explanation is that the star velocities remain high in response to much matter that we cannot see.

Where is it? Fritz Zwicky, over sixty years ago, discovered that in a cluster of galaxies like the Virgo Cluster, many individual galaxies are moving with velocities so large that galaxies should be leaving the cluster. But evidence that clusters are not dissolving led Zwicky to suggest that there is more matter in the cluster than can be seen, and this unseen matter is gravitationally holding the cluster together. Zwicky called this “missing mass.” However, astronomers now prefer the term “dark matter,” for it is the light, not the mass that is missing.

We know now that dark matter dominates the mass of both individual galaxies and also clusters of galaxies. Direct evidence for the high dark matter mass in galaxy clusters comes from the discovery of gravitational lensing. Light from background galaxies, passing through the dense core of an intervening cluster, is gravitationally deflected, and the background galaxy images are warped into arcs and rings. A recent Hubble Space Telescope view of this effect is shown in Figure 7. Thus massive clusters act as natural telescope that enhance the intensity of the light. Nature made telescopes before Galileo did.

How much is there? Now the questions get harder to answer. The best answer is “We don’t know.” The amount of matter in the universe is fundamental to understand whether the universe will expand forever, or the

Figure 7. Galaxy cluster Abell 2218. The arcs are gravitationally lensed images of background galaxies, whose light is distorted by the mass of the foreground cluster. Credit: A. Fruchter and ERO team, STScI.

expansion will halt, and perhaps even recollapse. The galaxy and the cluster observations offer evidence that almost all the matter in a galaxy is dark. But even this high fraction of unseen matter describes a universe of low density, a universe that will continue to expand forever. However, theoretical cosmologists prefer a universe of higher density, so that the amount of matter is just sufficient to ultimately bring the expansion asymptotically to a halt. Such a high-density universe is the basis of the inflationary model of the Big Bang.

What is it? This is the question that really exposes our ignorance. Production of particles following the big bang puts a limit on the number of conventional particles in the universe. This limit suggests that only a small fraction of the dark matter can be baryonic, that is, conventional matter such as the familiar elementary particles and atoms known on Earth and in stars. Whatever constitutes the baryonic dark matter, it must be invisible: faint stars in enormous quantities, too faint to have been detected, mini-black holes, brown dwarfs, dark planets. All of these possible candidates have been looked for, and not found in significant numbers.

Some of the dark matter must be of an exotic nature unlike the atoms and molecules that compose the stars, the Earth, and our bodies. These might be neutrinos which are not massless, or those particles dreamed up but not yet detected; axions, monopoles, gravitinos, photinos. Physicists are currently devising laboratory experiments in an attempt to detect these still unknown particles. Maybe none of these ideas are correct. Observational cosmology has taught us that our imaginations are very limited. Most cosmological knowledge has come not from thinking about the cosmos, but from observing it.

This is the universe that we describe today. It would be a mistake to believe that we have solved the problems of cosmology. We have not. There are surely major features of the universe we have not yet imagined. Someday humans on Earth will know if the universe will expand forever, if the expansion is accelerating or decelerating, if life is ubiquitous throughout the universe. Most important, they will attempt to answer questions we do not now know enough to ask.

RECENT TRENDS IN THE INTERPRETATION OF QUANTUM MECHANICS

ROLAND OMNÈS

Max Planck discovered the existence of quanta one century ago and the basic laws of this new kind of physics were found in the years 1925-1926. They have since withstood the test of time remarkably well while giving rise to a multitude of discoveries and extending many times their field of validity. Quantum mechanics was certainly the most important breakthrough in science in the past century with its influence on physics and on chemistry and beyond, including many features of molecular biology.

Almost immediately, however, it was realized that the new laws of physics required that the foundations of the philosophy of knowledge be drastically revised because quantum rules conflicted with various deep traditional assumptions in philosophy such as causality, locality, the realistic representation of events in space and time, and other familiar ideas. For a long time, the so-called Copenhagen interpretation provided a convenient framework for understanding the quantum world of atoms and particles but it involved at least two questionable or badly understood features: a conceptual split between quantum and classical physics, particularly acute in the opposition between quantum probabilism and classical determinism, and a mysterious reduction effect, the “collapse of the wave function”, both difficulties suggesting that something important was still to be clarified.

Much work is still presently going on about these foundations, where experiments and theory inspire and confirm each other. Some results have been obtained in the last two decades or so, probably important enough to warrant your attention and I will try to describe a few of them.

VON NEUMANN'S THREE PROBLEMS

I believe the best way to introduce the topic will be to show it in a historical perspective by going back to the work by Johann (later John) von Neumann. In a famous book, *Mathematische Grundlagen der Quantenmechanik,* published in 1932, he identified some basic problems.

It may be interesting to notice that von Neumann was a mathematician, indeed among the greatest of his century. This was an asset in penetrating the essentials in a theory, quantum mechanics, which can be characterized as a typical formal science; that is to say a science in which the basic concepts and the fundamental laws can only be fully and usefully expressed by using a mathematical language. He was in addition a logician and he had worked previously on the theoretical foundations of mathematical sets. That was also a useful background for trying to master the quantum domain where logical problems and possible paradoxes were certainly not easier than those arising from sets.

It is also worth mentioning that von Neumann had been a student of David Hilbert, and Hilbert's conception of theoretical physics was very close to the contemporany trends in research. He thought that a mature physical theory should rest on explicit axioms, including physical principles and logical rules, from which the theory had to be developed deductively to obtain predictions that could be checked by experiments.

Von Neumann contributed decisively (along with Dirac) to the formulation of the basic principles, unifying the linear character of quantum states with the non-commutative properties of physical quantities within the mathematical framework of Hilbert spaces and defining dynamics through the Schrödinger equation. He also made an important step towards "interpretation", but this is a protean word that must be explained. It can mean interpreting the abstract theoretical language of physics into a common-sense language closer to the facts and experiments, just like an interpreter would translate a language into another; but interpretation can also mean "understanding" quantum physics, notwithstanding a drastic epistemic revision if necessary. We shall use the word with both meanings but von Neumann's contribution, which we are about to discuss, was definitely a matter of translation.

He assumed that every significant statement concerning the behavior of a quantum system can be cast into the form of an "elementary predicate", a statement according to which "the value of some observable A lies in a range Δ of real numbers" (By now, this assumption has been checked in all kinds of circumstances). He also found, as a consequence of his investigations on quantum observables, that a predicate of that kind can always be associated with a definite mathematical object, namely a subspace of the Hilbert space or, equally as well, the operator of projection over the subspace. The main point in the second version is that a projection operator can only have two values ("eigenvalues"), which are 0 or 1. We are now accustomed from the logic of computers (to which von Neumann contributed later decisively) to the fact that 1 can mean "true" while 0 means "false", so that projection operators can implement Aristotle's rule for the definite truth of propositions while using a basically probabilistic theory.

The proposal was both deep and potentially useful, since it provided a convenient language for the description of physical events, a language that was, moreover, directly rooted in the principles of the theory. Its existence might have had a great influence on interpretation but, unfortunately, it was immediately disregarded because of three dire difficulties. Von Neumann himself observed them as follows:

1. After devising a model for a measurement where the system to be measured and the measuring apparatus both obey quantum mechanics, he found the apparatus to be generally in a state of superposition, representing one measuring result *and* other ones. Since measuring devices are macroscopic, this meant the existence of macroscopic superpositions if quantum mechanics is universal, whereas such states are never observed. This difficulty became famous a few years later when it was explained by Schrödinger with a cat included in the device.

2. Physics becomes classical at a macroscopic level, but classical properties are not simple predicates. They refer not to the range of values for *one* observable but generally to two non-commuting physical quantities such as position and momentum, whose values are given together within some range of possible error. Von Neumann did not succeed in extending to classical properties the translation of a predicate by a projection operator. It looked, therefore, as if his language was restricted to atoms and particles and was deprived of universality.

3. The last difficulty jeopardized in some sense the whole process: If every elementary predicate is considered as a possible proposition, the language makes no sense because it cannot satisfy the elementary rules of standard logic.

THREE ANSWERS

The progress that has recently been accomplished in interpretation is best expressed by saying that von Neumann's three problems have now been solved. Let us review the answers.

Macroscopic superpositions versus decoherence

The problem of Schrödinger's cat never existed because of a physical effect, which is called decoherence. Its origin is to be found in the fact that the wave function of a macroscopic object does not depend only on the few collective quantities which are effectively measured or controlled, such as the position of a pointer on a voltmeter dial or the electric potential in a computer memory. The wave function depends typically upon some 10^{27} degrees of freedom or so, to take care of the internal atoms, the electrons inside the atoms and outside, the atmosphere molecules around the object and photons in surrounding light. All these uncontrolled degrees of freedom describe what is called the *environment* of the object, although there is as much internal "environment" as external.

Decoherence is easy to understand if one thinks of a pointer on an old-fashioned voltmeter dial. Let us consider a case where the voltmeter registers the result of a quantum measurement and does it by having the pointer pointing vertically up or down according to the measurement result. The crux of the Schrödinger cat paradox is to deal with a quantum state where the two positions "up" and "down" are superposed and the possibility of observing interferences between the two positions.

But think of what really happens. When the pointer begins to move towards the "up" position, the atoms near the pointer axis suffer some sort of a cataclysm or, at least, their partial wave functions are strongly affected, with wild changes in their local phase. The same thing happens when the pointer moves towards the "down" position, except that the environment wave function has no reason to keep any sort of phase coherence with its value in the "up" motion. This is the decoherence effect, which suppresses every possibility of quantum coherence between "up" and "down", every kind of interferences between them: the state of the pointer is only *either* "up" *or* "down" as it would be in a standard probabilistic description.

After being recognized [1], the decoherence effect began to be investigated on models, from which quantitative results were first obtained: it is by far the most efficient quantum effect acting at a macroscopic level. Later, it was recognized as a more or less standard kind of irreversible process. For a long time, it could not be observed experimentally for a rather peculiar reason, because it is so quick that it has already acted before one can see it in action. Finally, it was observed not long ago, with excellent agreement between the predictions and the observations [2]. Clearly, older considerations about reduction (wave function collapse) must take this important result into account.

Classical properties versus mathematics

A powerful technique was developed by mathematicians in the seventies for studying linear partial differential equations and related topics. It is called “microlocal analysis” or “pseudo-differential calculus”. Two basic results from this theory have yielded an answer for the second von Neumann problem. The first is concerned with a classical property allowing large errors in position and momentum as compared with Heisenberg’s uncertainty limit. A theorem says that such a property of that kind cannot be associated with a unique projection operator in Hilbert space but anyway, it is very well represented, qualitatively and quantitatively, by a set of “equivalent” projection operators.

Another theorem says how quantum evolution acts on these representative operators, in a way reflecting almost exactly the evolution of the classical property under classical dynamics. It means in a nutshell that the old and rather fuzzy “correspondence principle” has been replaced by explicit and precise statements, which directly derive from the true principles (Hilbert space formalism and Schrödinger dynamics). Another way to express these results would be to say that the von Neumann language using projection operators is universal: it can describe classical physics, classical situations, just as well as it suits quantum properties. One must therefore certainly revise the Copenhagen standpoint according to which physics had to be split into a classical domain and a quantum one, both having independent laws except for the loose connection of “correspondence”.

Standard logic and consistent histories

The last problem, namely the apparent conflict between the language of projection operators and standard logic, has also been solved by finding the right “grammar” for the language, in terms of so-called “consistent histories" [3]. The idea is to restrict explicitly a description of physical events by expressing it through a time-ordered sequence of relevant statements, which are either predicates (about atoms and particles) or classical properties (about macroscopic devices: preparation and detection for instance). Each statement of either kind is associated with a projection operator. Explicit "consistency conditions", which are equations involving these operators and the initial state, make sure that there exists a probability distribution (on a "family" of histories reviewing the various possible occurrences). Quite remarkably, it was also found that standard logic holds inside such a family of consistent histories and no "exotic" logic is necessary for interpretation.

A simple example of how the theory works is provided by a famous example from an interference experiment: it is indeed logically impossible to assert that a photon (or an atom) went through a single arm of an interferometer, because the corresponding histories do not satisfy the necessary consistency conditions. Conversely, the language most frequently used in books and papers on physics, in which cautious rules cleverly avoid paradoxes, can be fully justified from the consistency of the underlying histories.

Finally, a strong connection between the three kinds of new results should be mentioned: decoherence ends up most often with a classical situation, and logical consistency is also most often a consequence of decoherence or of the recognized validity of classical physics.

A NEW INTERPRETATION

Using the answers to the three problems, interpretation can be cast into a completely deductive sub-theory inside the theory of quantum mechanics [4]. Its physical axioms have been already mentioned (i.e., the Hilbert space framework and Schrödinger dynamics) whereas the logical axioms amount to the use of von Neumann's language under the constraints of consistent histories. The well-known rules of measurement theory are among the main results and they have become so many theorems in this approach. A few other aspects are worth mentioning:

– Probabilities become still more intimately linked with quanta. In this approach, they appear first in the logical axioms (where they define logical implication) and from there on one can prove (in the resulting logic) the necessity of randomness among physical events. This new vision of probabilities may be rather deep but its implications are not yet fully appreciated.

– Three "privileged" directions of time must enter the theory: one in logic (for the time ordering of predicates in histories), one for decoherence (as an irreversible process), and the familiar one from thermodynamics. The three of them must necessarily coincide. The most interesting aspect of these results is certainly that the breaking of time reversal symmetry is not primarily dynamical but logical and a matter of interpretation, at least from the present standpoint.

– There is only one kind of basic laws in physics in this construction, and they are quantum laws. The validity of classical physics for macroscopic bodies (at least in most circumstances) emerges from the quantum principles. In particular, classical determinism can be proved to hold in a wide domain of application. Its conciliation with quantum probabilism is finally very simple if one notices that determinism claims essentially the logical equivalence of two classically meaningful properties occurring at two different times (one property specifying for instance position and velocity for a tennis ball at an initial time and the other property being similar for reception at a later time). Their logical equivalence holds *with a very small probability of error*. This very small (and known) probability of error allows determinism to assume a probabilistic character, although a very safe one.

PHILOSOPHICAL CONSEQUENCES

It should be stressed first of all that this approach brings nothing new concerning the reality of quantum properties. Complementarity is still there and even more so, because it is now a trivial consequence of the history construction. The most interesting philosophical consequences are therefore concerned with the understanding of classicality in the ordinary world of macroscopic objects or, in a nutshell: why is common sense valid?

The technical answer to this question lies in considering histories where only classically meaningful properties of every kind of macroscopic objects enter. There is no problem of complementarity with such histories and therefore no problem with reality: the set of consistent histories describing our common experience turns out to be unique, sensible (i.e. satisfying the relevant consistency conditions), and the logical framework resulting from the quantum axioms in these conditions is what we might call "common sense". *There is therefore no conflict between quantum theo-*

ry and common sense and the first implies the second, except that one should be careful not to extend excessively the domain where common sense is supposed to be valid.

More precisely, one may refine common sense by making explicit in it familiar and traditional philosophical assumptions: causality (or determinism), locality in ordinary space, separability (except for measurements of an Einstein-Podolsky-Rosen pair of particles), reality (as used in a philosophical discourse, i.e. the consistency of all the – classical – propositions one may assert about the – macroscopic – world). The fourth has just been mentioned and the three first share a common character: they are valid at a macroscopic scale, except for a very small probability of error (or invalidity). When one tries, however, to extend them towards smaller and smaller objects, the probabilities of errors keep growing and finally, when one arrives at the level of atoms and particles, these traditional principles of the philosophy of knowledge have such a large probability of error that they are plainly wrong.

There is a lesson in this: When dealing with *physis*, the principles that have been reached by science after much work stand on a much firmer basis that many traditional principles in the philosophy of knowledge. The concepts and laws of physics have been checked repeatedly and very carefully in a wide domain and, as indicated in this talk, they imply the validity of older more philosophical principles in ordinary circumstances. Conversely, the old principles are limited in scope and the purpose of understanding in their light the essentials of quantum mechanics is illusory. Some sort of a "premiss reversal" in the philosophy of knowledge is therefore suggested [5].

Open questions

Some important questions are still a subject of controversy. All of them revolve around a central one: why or how is there a unique datum at the end of a measurement? Some questions concerning the ultimate meaning of decoherence are very close to this problem of actuality, or objectification, and the diversity of the proposed answers is too wide for them to be mentioned here. My own inclination goes towards an apparently new direction, which is why I mention it, addressing myself particularly to the philosophers and theologians in this Academy. I wonder whether the question of actuality is a problem *in* physics or *about* physics. In the second case, it would open wide philosophical perspectives, the most obvious one being a renewal of the old question: up to what point does physics reach reality and, outside this reach, should it be said to preserve appearances? After all, everything we observe can be derived directly from the quantum principles except for the uniqueness of empirical reality, but this uniqueness can be shown to be logically consistent with the basic principles, or preserved by them. More generally, I think we should be more inquisitive about the essential role of mathematics in basic science, considering that we do not know conclusively what is the status or the nature of mathematics. One may question particularly the possible limits of the “Cartesian program”, according to which one assumes – perhaps too easily – the possibility of a mathematical description for every aspect of reality.

REFERENCES

[1]. H. D. Zeh, *Found. Phys.* 1, 69 (1970), reprinted in the book by J. A. Wheeler and W. H. Zurek, *Quantum theory and measurements,* Princeton University Press, 1983.
[2]. M. Brune, E. Hagley, J. Dreyer, X. Maître, A. Maali, C. Wunderlich, J.-M. Raimond, S. Haroche, *Phys. Rev. Lett.* 77, 4887 (1996).
[3]. R. B. Griffiths, *J. Stat. Phys.* 36, 219 (1984).
[4]. R. Omnès, *Understanding quantum mechanics*, Princeton University Press, 1999 (French version: *Comprendre la mécanique quantique,* EdP Sciences, Les Ulis, 2000).
[5]. R. Omnès, *Quantum philosophy*, Princeton University Press, 1999 (a translation by A. Sangalli of *Philosophie de la science contemporaine,* Gallimard, Paris, 1994, with added material).

CHRIST AND SCIENCE

PAUL CARDINAL POUPARD

Jesus Christ is the most fascinating person who has ever existed. It is worth getting to know Him more than any other person, and no human discipline could ever find a better subject to study. However, science, or at least experimental science as we know it today, has not paid much attention to Him. Scientists throughout history have been very interested in God, to such a degree that, paradoxically, scientists may be considered to be more religious than other intellectuals. This was the case not only in the past but also today. Copernicus, Galileo and Newton were deeply religious men. But even Einstein, Max Planck and Kurt Gödel felt the need to speak about God, and more recently Stephen Hawking, Roger Penrose, Steven Weinberg and Lee Smolin have said a great deal more about God, and perhaps even to God, than many philosophers and theologians of our time.[1] The existence of God is an ever-present challenge, even for those who simply want to deny it: is the God-hypothesis necessary or not to explain the world scientifically? And if one admits that there is one eternal, omniscient God, how can this fit into the image of the world that science offers? It is difficult to escape these questions, once one attempts to see the world in terms which are broader than strictly empirical data.

Scientists and Jesus

While scientists have studied and reflected on God, this has not been the case with Jesus. The question of the historical Jesus who is believed by

---

[1] Cf. R. Timossi, *Dio e la scienza moderna. Il dilemma della prima mossa* (Mondadori, Milan, 1999).

Christians to be truly God and truly human does not seem to have found a place in scientific reflection.

There were numerous attempts in the course of the twentieth century to approach the figure of Jesus 'scientifically', above all in exegesis and the various biblical sciences. These disciplines set themselves the task of studying the person, actions and sayings of Jesus not from the point of view of traditional interpretation, inasmuch as this was considered too partial, but with a new, scientific, rational method, which approached the object being studied, in this case the figure of Jesus, from a neutral point of view. We owe to these disciplines significant progress in understanding the historical circumstances in which Jesus and the first Christian communities lived, as well as the origins of the first Christian writings. However, these approaches to the figure of Jesus, though they claimed to be scientific, were often heavily laden with preconceptions and *a priori* philosophical positions, which definitely compromised the objectivity of their results. 'Scientific' critical exegesis tended to be critical of everything but itself and lacked a sound epistemological foundation. The claim that this kind of approach made to being 'scientific' aroused strong objections, not only among researchers trained in the empirical sciences but also among those trained in the humanities.[2]

More recently, other scientific disciplines have attempted to subject the figure of Jesus to the proofs of science. I am thinking of studies carried out on objects and relics which were presumed to have had contact with Jesus, in particular the analyses and tests carried out on the Turin Shroud in 1978 and, more recently, in 1998.[3] The results of some of these tests are still controversial and there was some criticism of the fact that they were carried out at all. Clearly, a scientific investigation carried out on these objects will never provide absolute proof that they belonged to Jesus, much less prove that He existed. On the other hand, it is also true that these relics of Jesus, despite being very important and worthy of veneration by Christians, are not an object of faith in the strict sense. However, such investigations can help to give support, on a rational basis, to the authenticity of certain relics or facts linked to the figure of Jesus. They can also help to identify and

---

[2] Cf. J. Ratzinger *et al.*, *Schriftauslegung im Widerstreit* (Herder (*Quaestiones disputatae* 117) Freiburg, 1989).

[3] See, for example, E.M. Carreira, "La Sábana Santa desde el punto de vista de la Física" and J.P. Jackson, "La Sábana Santa ¿nos muestra la resurrección?" in *Biblia y Fe*, XXIV (1998).

avoid those that are false. Studies like these are always ultimately based on the desire to come to a rationally based knowledge of the case of Jesus, something which Christianity has always claimed to have as the *religio vera.* Faith has nothing to fear from reason,[4] so science can never be a threat when it wants to investigate Jesus. Anyone who has visited the Holy Land will know that, next to every church or sanctuary, and often under them, there is an archaeological dig, which is an attempt, in that particular context, to verify rationally what has been handed down as part of tradition. One can only hope that such research will be extended to many more objects or facts that are said to be miraculous. In these cases, science can help faith to rid itself of the leftovers of superstition and find solid foundations for belief.[5]

Obviously, these investigations touch Jesus Christ only indirectly, even though, when they speak of the resurrection of Jesus, it is impossible not to ask oneself about Him. Nevertheless, the link between Christ and science and scientists is still largely unexplored. One important lacuna is that there is no serious study on what Christ means for scientists, a thorough treatment of the way scientists have contemplated Christ across the centuries, and how they have approached Him. Father Xavier Tilliette did such a thing for philosophers in his book *Le Christ de la philosophie*, the sub-title of which is quite significant: *Prolégomènes à une christologie philosophique.*[6] The prolegomena for a similar 'scientific Christology' have still to be written.

Allow me to refer *en passant* to one very noteworthy attempt made in this area: Father Pierre Teilhard de Chardin's work entitled *Science and Christ.*[7] It was only an attempt, and it may well have attracted some criticism, but it was a noble effort on the part of one of the twentieth century's great anthropologists to bring his scientific knowledge face to face with

---

[4] John Paul II, 'Address to those who took part in the Jubilee of Men and Women from the World of Learning, 25 May 2000'.

[5] 'Science can purify religion from error and superstition'. Cf. John Paul II, 'Letter to Father George V. Coyne, 1 June 1988'. The text is in Pontificium Consilium De Cultura, *Jubilee for Men and Women from the World of Learning* (Vatican City, 2000), p. 59.

[6] X. Tilliette, S.J., *Le Christ de la philosophie* (Cerf, Paris, 1990). See the same author's *Le Christ des philosophes*, (Institut Catholique de Paris, Paris, 1974).

[7] P. Teilhard de Chardin, 'Science et Christ', a conference held in Paris on 27 February 1927. It was published in *Science et Christ* (Œuvres de Teilhard de Chardin, IX, Paris, 1965), pp. 47-62. See also E. Borne, 'Teilhard de Chardin', in P. Poupard (ed.), *Grande Dizionario delle Religioni* (Piemme, Casale Monferrato, 3rd. edn., 2000), pp. 2125ff.

Christ. In his study of matter, this great Jesuit anthropologist perceived a strong urge to unification and synthesis, an excess of energy which enabled matter to transcend itself more and more. He saw this as evidence of a process which would culminate in Christ. Teilhard was obviously not so naïve as to try to deduce Christian doctrine from the simple study of the properties of matter. He wrote that science, left to itself, cannot discover Christ, but Christ fulfils the desires which arise in our hearts when we are at the school of Science.[8] For Teilhard, Christ was so much a part of nature, as a unifying element, that he did not always acknowledge Christ's individuality. But at least he was looking in the right direction in his attempt to build a bridge between scientific research and the person of Christ.

Christianity recognises that Christ is the incarnate *Logos*. The divine *Logos* is the *Mind of the Universe*,[9] to use the provocative expression Mariano Artigas borrowed from Seneca. With its affirmation that, in the beginning, there was the *Logos*, Christianity invests in the rationality of the universe rather than in chaos. It builds a bridge that links the intelligibility of nature – which is what makes science possible – with the designer of the universe. As a matter of fact, the rationality of nature is a necessary precondition for scientific activity. It is a hypothesis which cannot be proved scientifically, but it is, nonetheless, indispensable for the very existence of science. Far from dismissing this hypothesis, scientific progress seems to prove its substantial correctness and to broaden its significance.[10] Paul Davies conceded that 'one cannot prove the world to be rational...Yet the success of science is at the very least strong circumstantial evidence in favour of the rationality of nature.'[11] The recovery of the concept of *Logos* applied analogously to Him who is hypostatically the *Logos*, and to its participation in created beings, is thus revealed as a rich and promising idea which ought to be further explored in order to link Christ with nature in a coherent and articulate way. To avoid confusion, this ought to be done with-

---

[8] 'La Science, seule, ne peut découvrir le Christ, mais le Christ comble les voeux qui naissent dans notre coeur à l'école de la Science', in 'Science et Christ', p. 62.

[9] M. Artigas, *The Mind of the Universe* (Templeton Foundation Press, Philadelphia-London, 2000), pp. xx ff. Seneca uses the expression in *Quaestiones Naturales* I, 13.

[10] M. Artigas, 'Science et foi : nouvelles perspectives', in P. Poupard (ed.), *Après Galilée (*Desclee, Paris, 1994), p. 201. Cf. J. Ladrière, 'Scienza-Razionalità-Credenza', in P. Poupard (ed.), *Grande Dizionario delle Religioni* (Piemme, Casale Monferrato, 3rd. edn., 2000), pp. 1942-1947.

[11] P. Davies, *The Mind of God: The Scientific Basis for a Rational World (*Simon & Schuster, New York & London, 1993), p. 191.

out turning Christ into some sort of soul of the universe and at the same time avoiding a radical separation where Christ has no place in nature.

The Science of Christ

I would like to approach the subject assigned to me in another way: by revisiting the mediaeval question known by the title *De Scientia Christi,* which refers to Christ's knowledge, the sort of knowledge Christ himself had. I realise this terminology may appear bizarre and far removed from the kinds of questions people like yourselves face every day in your work. I am well aware of the risk involved, but I would still like to make a tentative incursion into the rich mystery which is the person of Christ, and to draw out what is relevant to the ever-present question of the links between science and faith.

For the Christian Faith, Christ, who is God incarnate, is truly God and truly human. As such, he possesses the fullness of divine nature and of human nature, each with its respective properties. As far as knowledge is concerned, this means that, as God, Christ had a knowledge of reality which was divine, in other words perfect, infinite and all-embracing. At the same time, as a human being he had a mode of knowing which was human, and therefore limited, susceptible to experience and change. In the Middle Ages, people's approach to this question was not driven by an interest in history or by a preoccupation with studying the parts of the Bible which addressed this subject. They had a strictly speculative approach to what they saw as a philosophical problem. For them it was more a sort of *Gedankenexperiment,* a mental exercise, but one whose point of departure was a datum of faith: the historical person of Jesus of Nazareth, a first-century Jew, whom they believed to be both divine and human. If we align ourselves with that perspective, either by accepting the hypothesis that there existed such a being with both the mind of God and the brain of a human being, or because we believe in Him, the question of Christ's knowledge – *scientia Christi* – puts before us a vast range of unresolved questions: the possibility of infinite and perfect knowledge, the limits of human knowledge, the incarnation of that sort of divine intelligence within the limits of the ontological horizon of the finite. These are all variants, perhaps extreme ones in some cases, of the modern question *par excellence,* the question of the essence of knowledge.

Inasmuch as He was the incarnate Word and God – "The Father and I are one" (*Jn* 10.30) – Jesus had an infinite divine intellect, which missed no detail. But the idea of an infinite intellect capable of knowing infinite things has posed numerous problems, which were studied during the past century by Kurt Gödel in his incompleteness theorems. The first problem is to find out whether infinite things exist, or, in other words, whether there is something infinite which actually exists rather than a merely potential infinite. Knowledge of an actual infinite thing poses a further problem: if an intellect is able to know and comprehend something infinite, the very fact of comprehending it imposes a limit on it, since the knowledge would be a greater infinite thing than the infinite known – the universe. Then there is the whole question of whether the infinite holiness of God is compatible with infinite knowledge, one of whose objects would be evil.[12] These are but a few of the questions which arise from a consideration of the divine intellect. But they become even more difficult when one considers what happened in the Incarnation, when God decided to lower Himself and allow Himself to be enclosed within the narrow limits of a human nature (cf. *Phil* 2.5-11).

Jesus, who was known as the carpenter's son, was a man with a human intellect. He had a brain, with neuronal connections which allowed Him to think, to have ideas, to express emotions and to hazard guesses. But there is still the whole question of knowing what link there was between his divine capacity for knowing the world and his human intelligence with all its limits. The human element in Christ's knowledge is known in mediaeval terminology as 'experimental knowledge', which He acquired throughout his life. The Gospels actually tell us that Jesus grew 'in wisdom, in stature, and in favour with God and men' (*Lk* 2.52). He was also painfully shocked by the lack of faith of the people from his home-town of Nazareth (*Mk* 6.6). But only someone who did not know everything and expected a different reaction would be capable of such amazement. The man Jesus did not know everything. He Himself admitted that He did not know anything about certain aspects of God's plan for saving the world: "as for that day and hour, nobody knows it, neither the angels of heaven, nor the Son, but the Father only" (*Mt* 24.36). That text encapsulates a problem which has always perplexed theologians: how can it be that Jesus, who was God and had infinite knowledge, and therefore could even know the future, said that He did not know the date of the end of the world? It

---

[12] See, for example, Saint Bonaventure's *Quaestiones disputatae de Scientia Christi,* in the recent edition by F. Martínez Fresneda, ITF (Murcia 1999), and the very interesting introduction by M. García Baró.

is his human, experimental knowledge, which also makes Him closer to us. The Jesus who is speaking here is the man who has learned from his teachers how to read the book of the Law and the book of Nature, both of which He turns out to know very well.

Jesus and the Science of his Time

Perhaps it is opportune at this point to make a few remarks about the kind of scientific knowledge Jesus had, or at least about his attitude to science. At first glance, Christ does not appear to think science is terribly important. In fact, He appears to see it as an obstacle to entering the Kingdom of heaven. He even says, "I bless you, Father, Lord of heaven and earth, for hiding these things from the learned and the clever and revealing them to mere children" (*Lk* 10.21). He deliberately picked his close associates from people who were not very well educated (*Acts* 4.13), and asked St. Paul to give up the arguments of persuasive reason (*1 Cor* 2.4). But it would be wrong to think that, in this way, he looked down on scientific research. In these cases he was emphasising the primacy of love and the superiority of that knowledge which comes from God, in order to topple human pride which always tries to take God's place through a Promethean urge. Jesus also taught the parable of the talents (*Mt* 25.14-30) to stimulate self-improvement in every aspect of our lives, which would include science. Whoever refused to learn would be like the lazy servant who hid his talent and was condemned for it by his master (verses 26-27). Christ never refuted the teachings of the Old Testament and the Wisdom Literature where the study of nature and of human values has an important role. The more human beings get to know nature, the more they will praise its Author (*Wis* 13.2-5). Besides, the man Jesus knew a certain amount about some phenomena in nature – albeit in a limited way and subject to the conditioning of the time when He lived. He grew up in a rural area, so it is obvious that there would be images taken from the natural world in his teachings. Jesus knew and spoke about the cycles of life, especially in agriculture. He knew that plants grow from seeds (*Mk* 4.1ff.), and that they develop of their own accord (*Mk* 4.27). While he admitted that He knew little about the actual mechanisms involved in the development of seeds, their growth is never ascribed to spirits, or even to God, but to the power of nature itself. Perhaps the passage which reveals a more accurate degree of scientific knowledge is the one in which Jesus makes the connection between various atmospheric phenomena. "In the evening you say, 'It will be fine; there is a red sky', and in the morning, 'Stormy weather today; the sky is red and overcast" (*Mt* 16.2f.). Jesus scolded the people from His home town because, while they could read the face of the sky, they were unable to read the signs of his coming. But what He said contains a clear allusion to a certain accumulated experience of observing the atmosphere and, by implication therefore, to the intelligibility of nature.

These are only very weak indications, but they do still reveal the man Jesus as someone who observed nature carefully, someone who was curious about the phenomena surrounding life in the countryside, and someone who could draw from the book of nature teachings for living. There are just a few hints elsewhere in the Gospel about the scientific activity of those times. There is a reference to what doctors do. The evangelist Mark is quick to point out that a poor widow had suffered a great deal at the hands of doctors whose services had cost her all her money, but Luke – the doctor so dear to St. Paul (*Col* 4.14) – may be speaking with a certain sympathy and *esprit de corps* when he says that nobody had been able to cure her. Even astrologers, to whom we owe the beginnings of the science of astronomy, have a special place in the life of Jesus, since they were the first non-Jews to adore the new-born baby. The wise men from the east were known as 'Magi', a term that is quite vague, but conjures up the image of someone who studies the heavens. In recognising the coming of the Messiah, they stole a march on Israel's wise men, the experts on the Scriptures. This marks a clear victory for scientists over theologians. The one who declared Himself to be the Truth could surely never refuse those who struggle in their search for a better knowledge of nature, life and the world.

Faith and Reason: the Two Ways to Reach the Truth

In Jesus there are two modes of knowledge which differ in nature but have the same object. That is why He is able to say He is one with the Father, and yet admit that He does not know when the hour of judgement will come. As *Logos*, He is the creative wisdom which was there at the beginning of creation, as its architect (*Prov* 8.30), and yet He is unaware of how the seed sown by the sower grows. In Christ, divine knowledge and experimental knowledge are not opposed to each other, nor do they cancel each other out. They are different modes of knowledge which are united without confusion or change, without division or separation, according to the formula used by the Council of Chalcedon to describe the relationship between the two natures of Christ (*DS* 302).

In this way Christ Jesus is an extreme case of the relationship within the human person between faith and reason, and between science and faith. What there is in Christ in a unique and special way, the unity of two natures in a single hypostasis or person, is replicated analogously in Christians. Faith is the way they participate in the knowledge of God, which He Himself has revealed. Faith is, therefore, seeing things in God's own light. Faith also opens up a broad field of objects which would otherwise be inaccessible to human knowledge; the disputed questions on the *Scientia Christi* are an example of this. But faith never replaces experimental knowledge, which human beings acquire by their own efforts, as they attempt to unravel the secrets of nature. Faith does not annul reason and reason does not expel faith. They are both like 'wings on which the human spirit rises to the contemplation of the Truth' (*Fides et Ratio* 1).

A right understanding of the links between science and faith is absolutely essential if scientists are to avoid foundering in dire straits, steering clear as much of the Scylla of fideism as of the Charybdis of scientism, and if they are to avoid denying the problem by taking refuge in syncretistic solutions. Fideism[13] thinks it can save faith by denigrating the capacity of human reason to reach the truth, and it has been a defence mechanism used by many believers in the face of scientific progress. But to deny reason its rights in order to save faith always impoverishes faith, which is then forced into pious sentimentality. Christianity's original claim was that it was the *religio vera*, that it possessed a truth about the world, history and humanity which would hold up in the face of reason. I like to remember what Chesterton said about going to church. We take off our hats, but not our heads.

This attitude crops up in another guise, in a sort of exhumation of the mediaeval theory of twin truths, whereby faith and reason each have their own province of knowledge, and it is thus possible to deny in one what one could affirm in the other. Scientists who were also believers have often adopted this compromise solution in order to deal with what they saw as an insurmountable conflict between the biblical account of creation and evolutionary theories. This means living in two separate worlds which can never be on a collision course because there is no contact between them. But this is yet another form of fideism which denies not

---

[13] See my article 'Fideismo', in *Grande Dizionario delle Religioni* (Piemme, Casale Monferrato, 3rd. edn., 2000), pp. 753ff, and my *Un essai de philosophie chrétienne au XIX siècle. L'abbé Louis Bautain* (Paris, 1961).

the capacity of reason, but its right to enter into dialogue with revelation and faith.

The other danger which threatens the work of scientists is the temptation of scientific reductionism, or the belief that science is the only acceptable form of knowledge. Buoyed up by the unstoppable conquests of science, the scientist may play down other dimensions of human knowledge, regarding them as irrelevant. This applies not only to faith, but also to philosophy, literature, and ethics. Science needs to be open to other disciplines and to be enriched by data that come from other fields of investigation.[14] Science is not capable of explaining everything. Paul Davies admits as much in *The Mind of God*, when he says that his desire to explain everything scientifically always comes up against the old problem of the chain of explanations. For him, ultimate questions will always remain beyond the realm of empirical science.[15] I am happy to recall the symposium entitled *Science in the Context of Human Culture*, organised jointly by the Pontifical Council for Culture and the Pontifical Academy of Sciences in October 1990. Its great richness lay in its exploration of the need for greater interdisciplinary co-operation between scientists, philosophers, and theologians. Let me renew today the appeal I made then for dialogue, which becomes more and more difficult the more people's work becomes specialised. The remarkable experience of dialogue in those few days was formulated much more recently in the Pontifical Council for Culture's document *Towards a Pastoral Approach to Culture* (Vatican City 1999):

> In the realm of knowledge, faith and science are not to be superimposed, and their methodological principles ought not to be confused. Rather, they should overcome the loss of meaning in isolated fields of knowledge through distinction, to bring unity and to retrieve the sense of harmony and wholeness which characterizes truly human culture. In our diversified culture, struggling to integrate the riches of human knowledge, the marvels of scientific discovery and the remarkable benefits of modern technology, the pastoral approach to culture requires philosophical reflection as a prerequisite so as to give order and structure to this body of knowledge and, in so doing, assert reason's capacity for truth and its regulatory function in culture (no. 11).

---

[14] Cf. Paul Poupard, *Science in the Context of Human Culture II* (Pontifical Academy of Sciences-Pontifical Council for Culture, Vatican City, 1997).

[15] Cf. *The Mind of God* (Simon & Schuster, London, 1992), pp. 14, 15, 232.

Scientia Christi

My dear and learned friends, we have spent time together along the intricate paths of human knowledge. Having spoken at length of Christ and science, I feel obliged to offer one final reflection on the knowledge of Christ: not on what He knew, but on the science which has Him as its object, the true science of life.

On this subject, I am reminded of some words spoken some forty years ago by Paul VI. It was in 1963. Paul VI had just been elected Pope and was welcoming the Members of the Pontifical Academy of Sciences for the first time. Perhaps some of you were present, along with me, then one of the Pope's youngest colleagues. He expressed his joy over a stimulating certainty: 'the religion we are happy to profess is actually the supreme science of life: thus it is the highest and most beneficial guide in all the fields where life manifests itself'. He concluded by developing a very beautiful thought: 'religion *may appear to be absent* when it not only allows but requires scientists to obey only the laws of life; but – if we look more closely – religion will be at their side to encourage them in their difficult task of research, reassuring them that the truth exists, that it is intelligible, that it is magnificent, that it is divine'.[16] Christ *may appear to be absent*, but He is not. Ladies and gentlemen, in this Jubilee Year, dedicated to Jesus Christ, allow me to invite you most sincerely to do all you can to acquire this supreme science.

---

[16] Paul VI, 'Discorso alla Sessione Plenaria della Pontificia Accademia delle Scienze, 13 October 1963', in Pontificia Academia Scientiarum, *Discorsi indirizzati dai Sommi Pontefici Pio XI, Pio XII, Giovanni XXIII, Paolo VI, Giovanni Paolo II alla Pontificia Accademia delle Scienze dal 1936 al 1986* (Vatican City, 1986), pp. 109-111.

ON TRANSDISCIPLINARITY

JÜRGEN MITTELSTRASS

In my contribution on "Science as Utopia" at the Preparatory Meeting last year, I touched upon the concept of transdisciplinarity, pointing to the fact that research is moving beyond its disciplinary limits. Let me add a few remarks and observations to this concept.

In the course of a long institutional route, our academic system has become disturbingly unfathomable.[1] This is the case not only with regard to the ever accelerating growth of knowledge in all scientific fields, but also with regard to the organisational and institutional forms of academic research. There is an increasing particularisation of disciplines and fields; whereas the capacity to think disciplinarily – that is, in terms of larger theoretical units – is decreasing.

Thus it is no surprise that there has been much talk about the desirability of interdisciplinarity, and this for some time now. Sitting alone on one's disciplinary island, one is likely to be drawn to one's mates on neighbouring islands, and it is perhaps not so important who these disciplinary neighbours are. The borders between fields and disciplines, to the extent that they are still observed at all, threaten to become less institutional borders than *cognitive* ones. And thus the concept of interdisciplinarity comes to include the notion of an improvement, which should lead in time to a new scientific and academic order. Interdisciplinarity is in consequence neither something normal, nor indeed something really new, nor simply the scientific

---

[1] For the following, cf. J. Mittelstrass, "Interdisziplinarität oder Transdisziplinarität?", in: L. Hieber (ed.), *Utopie Wissenschaft. Ein Symposium an der Universität Hannover über die Chancen des Wissenschaftsbetriebs der Zukunft (21./22. November 1991)*, Munich and Vienna 1993, pp. 17-31, also in: J. Mittelstrass, *Die Häuser des Wissens. Wissenschaftstheoretische Studien*, Frankfurt/Main 1998, pp. 29-48.

order itself. When it succeeds, it corrects defective academic and theoretical developments, thereby making clear that we have lost the capacity to think in larger disciplinary units. A coherent whole should be regenerated out of particularities, and we should thereby regain something that was the academic norm in the history of European academic institutions before the “discovery” of interdisciplinarity. Nevertheless, it is not this “institutional” perspective, that is to say the re-establishing of real disciplinarities, that should be in the foreground here, but instead the role of structures and strategies in research extending beyond fields and disciplines (and thus indirectly in teaching as well).

Here one should first make clear that these fields and disciplines came into being in the course of the history of the sciences, and that their borders are founded primarily neither in objects nor in theory, but are historical as well. At the same time, their historical identities are shaped by definite research objects, theories, methods, and goals, which often do not comprise a coherent disciplinary definition, but in fact *interfere* interdisciplinarily. This is expressed not only in the fact that disciplines are governed in their work by methodological and theoretical concepts, which cannot themselves be generated within each discipline, but also in the fact that the problems addressed by academic disciplines often cannot be enclosed within a single disciplinary frame. Thus in the history of the theoretical description of Heat, for instance, disciplinary responsibility often changed. At first, Heat was considered as an internal motion of matter and thus as an object of physics. It became an object of chemistry, however, in the light of the caloric theory formulated by Boerhaave at the beginning of the eighteenth century and later developed by Lavoisier, since it was then considered to be a kind of matter. Finally, Heat changed its disciplinary allegiance yet again with the kinetic theory, and once more became an object of physics. This shows that it is not the objects (alone) which define a discipline, but the manner in which one deals with them theoretically. This is often clear enough in the context of research, but not necessarily in teaching.

This example from the history of science can be generalised so as to show that there are certain problems that escape the confines of a single discipline. Far from being marginal ones, these are often central problems, like, for example, the environment, energy and health. There is an asymmetry between the development of problems and that of disciplines, and this asymmetry is accentuated by the fact that the development of fields and disciplines is determined by increasing specialisation. Ecological problems are complex, and they may be solved only through the co-operation of many disciplinary competencies. The same is true of energy and health. But this means that the term interdisciplinarity is concerned not merely with a fashionable ritual, but with forces that ensue from the development of the problems themselves. And if these problems refuse us the favour of posing themselves in terms of fields or disciplines, they will demand of us efforts going as a rule well beyond the latter. In other words, whether one understands interdisciplinarity in the sense of re-establishing a larger disciplinary orientation, or as a factual increase of cognitive interest within or beyond given fields or disciplines, one thing stands out: interdisciplinarity properly understood does not commute between fields and disciplines, and it does not hover above them like an absolute spirit. Instead, it removes disciplinary impasses where these block the development of problems and the corresponding responses of research. Interdisciplinarity is in fact transdisciplinarity.

While scientific co-operation means in general a readiness to co-operation in research, and thus interdisciplinarity in this sense means a concrete co-operation for some definite period, transdisciplinarity means that such co-operation results in a lasting and systematic order that alters the disciplinary order itself. Thus transdisciplinarity represents both a form of scientific research and one of scientific work. Here it is a question of solving problems external to science, for example the problems just mentioned concerning the environment, energy or health, as well as a principle that is internal to the sciences, which concerns the order of scientific knowledge and scientific research itself. In both cases, transdisciplinarity is a research and scientific principle, which is most effective where a merely disciplinary, or field-specific, definition of problematic situations and solutions is impossible.

This characterisation of transdisciplinarity points neither to a new (scientific and/or philosophical) holism, nor to a transcendence of the scientific system. Conceiving of transdisciplinarity as a new form of holism would mean that one was concerned here with a scientific principle, that is to say a scientific orientation, in which problems could be solved in their entirety. In fact, transdisciplinarity should allow us to solve problems that could not be solved by isolated efforts; however, this does not entail the hope or intent of solving such problems once and for all. The instrument itself – and as a principle of research, transdisciplinarity is certainly to be understood instrumentally – cannot say how much it is capable of, and those who construct and employ it also cannot say so in advance. On the other hand, the claim that transdisciplinarity implies a transcendence of the scientific system, and is therefore actually a *trans-scientific* principle, would mean that transdisciplinarity was itself unbounded, or that it was bounded by arbitrary terms which were themselves beyond scientific determination. Put otherwise: transdisciplinarity is – and remains deliberately – a science-theoretical concept which describes particular forms of scientific co-operation and problem-solving, as opposed to forms lying outside of scientific boundaries. For what could be the point of looking to trans-scientific considerations, i.e. at relations lying outside the scope and responsibility of the sciences, to find an organising principle for the latter?

Furthermore, pure forms of transdisciplinarity are as rare as pure forms of disciplinarity. For the latter are most often realised and understood in the context of neighbouring scientific forms, for instance in the sociological components of a historian's work, or the chemical components of a biologist's. To this extent, disciplinarity and transdisciplinarity are also principles governing research, or ideal forms of scientific work, hybrids of their normal forms. What is important is only that science and academic research are conscious of this, and that productive research not be bounded by out-dated restrictions (which are mostly a product of routine) confining it to given fields or disciplines. Such a confinement serves neither scientific progress, nor the world which, in reflecting on its own problems, seeks less to admire science than to use it.

In other words, transdisciplinarity is first of all an integrating, although not a holistic, concept. It resolves isolation on a higher methodological plane, but it does not attempt to construct a "unified" interpretative or explanatory matrix. Second, transdisciplinarity removes impasses within the historical constitution of fields and disciplines, when and where the latter have either forgotten their historical memory, or lost their problem-solving power because of excessive speculation. For just these reasons, transdisciplinarity cannot replace the fields and disciplines. Third, transdisciplinarity is a principle of scientific work and organisation that reaches out beyond individual fields and disciplines for solutions, but it is no trans-scientific principle. The view of transdisciplinarity is a scientific view, and it is directed towards a world that, in being ever more a product of the scientific and technical imagination, has a scientific and technical essence. Last of all, transdisciplinarity is above all a *research principle*, when considered properly against the background I have outlined concerning the forms of research and representation in the sciences, and only secondarily, if at all, a *theoretical principle*, in the case that theories also follow transdisciplinary research forms.

What may seem quite abstract here has long found concrete forms in academic and scientific practice. Indeed it is being increasingly encouraged institutionally, for instance in the case of new research centres which are being founded in the USA, in Berkeley, Chicago, Harvard, Princeton and Stanford,[2] where a lot of money is in play. The “Centre for Imaging and Mesoscale Structures” under construction in Harvard calls for a budget of thirty million dollars for a building of 4.500m^2. Here scientists will be investigating questions it would be senseless to ascribe to a single field or discipline. The focus is on structures of a particular order of magnitude, and not on objects of a given discipline. And there are other institutional forms possible, which are not necessarily housed in a single building, for instance the “Centre for Nanoscience (CeNS)” at the University of Munich.

Such centres are no longer organised along the traditional lines of physical, chemical, biological and other such institutes and faculties, but from a transdisciplinary point of view, which in this case is following actual scientific development. This is even the case where individual problems, as opposed to wide-scope programmes, are the focus, as for example in the case of the “Bio-X”-Centre in Stanford[3] or the “Centre for Genomics and Proteomics” in Harvard.[4] Here, biologists are using mature physical and chemical methods to determine the structure of biologically important macro-molecules. Physicists like the Nobel-prize-winner Michael Chu, one of the initiators of the “Bio-X” programme, are working with biological objects which can be manipulated with the most modern physical techniques.[5] Disciplinary competence therefore remains the essential precondition for transdisciplinarily defined tasks, but it alone does not suffice to deal successfully with research tasks which grow beyond the classical fields and disciplines. This will lead to new organisational forms beyond those of the centres just mentioned, in which the boundaries between fields and disciplines will grow faint.

Naturally this holds not just for university research, but for all forms of institutionalised science. In Germany, for instance, these present a very diverse picture, which ranges from university research, defined by the unity of research and teaching, to the Max Planck Society’s research, defined by path-breaking research profiles in new scientific developments, to large-

---

[2] Cf. L. Garwin, “US Universities Create Bridges between Physics and Biology”, *Nature* 397, January 7, 1999, p. 3.

[3] Cf. L. Garwin, *ibid*.

[4] Cf. D. Malakoff, “Genomic, Nanotech Centers Open: $200 Million Push by Harvard”, *Science* 283, January 29, 1999, pp. 610-611.

[5] Cf. L. Garwin, *ibid*.

scale research, defined by large research tools and temporally constrained research and development tasks (that were earlier quite openly announced as lying in the national interest), to industrial research, defined through its tight connection between research and development.

But the logic of such a system, which bears witness not only to scientific reason, but also to extraordinary efficiency, is becoming problematic. For it leads to the autarchy of the component systems, whereas in fact – as in the case of the new centres I just mentioned – the emphasis should be on networking at the lowest institutional level, and not on the expansion of independent systemic units on the high institutional plane. This means that temporary institutionalised research co-operatives should take the place of component systems which are increasingly opposed and isolated. And this can be easily justified from the point of view of the sciences: *The scientific system must change, when research changes.* At the moment, the situation is often rather the reverse: It is not research that is searching for its order, but rather an increasingly rigid order which is already laid out in component systems that is searching for its research. And in such a case, the scientific order becomes counterproductive. This cannot be the future of research, or of a scientific system. As we have seen, the increasing transdisciplinarity of scientific research has wide-ranging institutional consequences – at least it ought to have them.

‘ILLICIT JUMPS’ – THE LOGIC OF CREATION

MICHAEL HELLER

1. In spite of the many breath-taking achievements in neuroscience we still do not know the most important thing of all: how do neural signals become transformed into consciousness? The following remarks are aimed at expressing this ignorance in a quasi-logical way. It is essential to clearly know what (and how) we do not know. This seems to be a precondition to even starting to move in the right direction.

2. The logic of language is traditionally divided into three parts: (1) *syntaxis*, which investigates the relations between the expressions of a given language; (2) *semantics*, which investigates the relations between a language and what that language refers to; and (3) *pragmatics*, which investigates the relations between the expressions of a language and its users. Syntactic investigations remain inside the language, whereas semantical and pragmatic investigations go from the language to the world it describes and to the people who speak it, respectively. In the following paper, I shall base my considerations on the interplay between syntaxis and semantics, putting aside, for the time being, their pragmatic aspect. After all, pragmatics is certainly a less developed branch of the logic of language.

3. There exist languages which completely lack a semantic aspect. They are purely formal languages and are often called artificial languages. In all other languages syntaxis and semantics are in a constant interplay with each other. Terms such as ‘meaning’, ‘reference’, and ‘denotation’ are semantic terms, or better, ‘semantic operators’. They ‘act’ on the language, and have their ‘values’ in the world the language describes. Owing to such operators a given language can be a language about something.[1]

---

[1] Sometimes one speaks about a meaning in relation to purely formal languages but, in such a case, the meaning of a given expression is to be inferred from the rules of how this expression is used within the language.

4. It can happen that a language refers to itself. If we treat a reference as a semantic operator then this language operates on itself. Strictly speaking, we should distinguish here two languages: the language that operates – which is called a 'metalanguage' (or the language of the second order) – and the language which is operated on: this is just called 'language' (or the language of the first order). There can be languages of many orders.

Here we must be on our guard against sophisticated traps. On the one hand, jumping from a language to the metalanguage (or *vice versa*) can create antinomies (the so-called semantical antinomies) such as, for example, the famous antinomy of the liar ("what I am saying now is a lie" – is this statement true or false?). On the other hand, however, a skilful manipulating of the languages of various orders can be a very efficient method by which to prove subtle theorems related to the foundations of logic and mathematics. For instance, Kurt Gödel proved his outstanding incompleteness theorem by, first, translating utterances about arithmetics into numbers, then by performing arithmetical calculations on these numbers, and finally by translating the obtained results back into the language about arithmetics. This strategy is called the 'self-reference method', and nowadays is more and more appreciated. In general, however, jumping from one linguistic level to another linguistic level, if done without a rigorous logical control, is dangerous and trouble-generating.

5. In fact, this rigorous logical control is possible only as far as purely formal languages are concerned. Although, in principle, such languages have no semantics at all, semantics can be 'artificially' attached to them, and precisely because it is 'artificial' we obtain full control of the process. This is done by creating an *interpretation* of a given purely formal language. The truly ingenious idea is to create a purely formal linguistic substitute of the reality the language has to describe. This substitute is called a (*semantical*) *model* of a given language (I shall not here go into technical details). When such a model is created we say that the considered formal language has acquired its (*semantic*) *interpretation*. Having at our disposal a formal language and its model, the rules of going from the language to its model, and *vice versa*, can be fully codified. To do this is the principal goal of semantics. Tarski's famous definition of truth says that an utterance (belonging to a given formal language) is true if and only if it asserts something about its model and this really occurs in the model.

However, if we go beyond the realm of formal languages a mess dominates the scene. Almost every transition from syntaxis to semantics (and *vice versa*), is from the point of view of strict logic an 'illicit jump'. In spite of this, we all speak natural languages and surprisingly often we understand each other (with a degree of accuracy sufficient to act together and communicate with each other). But this is a pragmatic side of the story which I have decided to put to one side.

6. In traditional philosophy, going back to medieval scholasticism, there was a fundamental distinction between the epistemological (or logical) order (or level) and the ontological order (or level). It roughly corresponded to the modern distinction between syntaxis and semantics with a shift of emphasis from the *relationship between language and what it describes* (the modern distinction) to the relationship between 'what is in the intellect' and 'what is in reality' (the traditional distinction). The latter distinction appeared, for example, in the criticism by St. Thomas Aquinas of the famous 'ontological argument' for the existence of God proposed by St. Anselm of Canterbury. 'God is something the superior of which cannot be thought of (*aliquid quo nihil majus cogitari possit*). And what does exist is greater than what does not exist. Thus God does exist' – claimed St. Anselm. St. Thomas did not agree: the statement 'God is something the superior of which cannot be thought of' belongs to the epistemological order, whereas 'God does exist' belongs to the ontological order, and the 'proof' consists of the 'illicit jump' between the two orders. This distinction became one of the corner stones of the Thomist system and was strictly connected with its epistemological realism. Discussions like that between St. Anselm and St. Thomas (and its continuation by Descartes, Leibniz and Kant) paved the way for the modern logical analysis of language.

7. Strangely enough, modern tools of linguistic analysis can be used to more effectively understand the functioning of the universe, or, more strictly, to see more clearly where the gaps in our knowledge of it are located. The point is that nature seems often to employ linguistic methods in solving some of its fundamental problems. I shall briefly touch upon three domains in which this 'linguistic strategy' of nature can be seen quite transparently. All these domains are in fact fundamental as far as our understanding of the world is concerned.

8. The first of these domains is the genetic code. In fact 'code' is here a synonym for 'language'. As is well known, it consists of linear strings of only four bases playing the role of letters in the 'alphabet of life'. 'The linear sequence of these four letters in the DNA of each species contains the information for a bee or a sunflower or an elephant or an Albert

Einstein.'[2] This is clearly the syntactic aspect of the genetic code. The point is, however, that the 'syntactic information' must be implemented within the biological machinery. Syntaxis must generate semantics. And do even more than this. After all, living beings are not purely linguistic concepts, but things that are real. For this reason, the old philosophical vocabulary about the epistemological and ontological orders seems to be more adequate in this context. The vocabulary *but not the rules* of traditional philosophy! The phenomenon of life testifies to the fact that, contrary to these rules, the 'illicit jump' from the epistemological order to the ontological order has been made. The genetic code does not only describe certain modes of acting, but also implements the action within the concrete biological material.

Jacques Monod sees this 'semantic antinomy' in the following way. The biological code would be pointless without the possibility of being able to decode it or to translate it into action. The structure of the machine which does that is itself encoded into the DNA. The code cannot be decoded unless the products of the code itself are involved. This is the modern version of the old *omne vivum ex ovo*. We do not know when and how this logical loop was closed.[3]

9. Another domain in which nature uses linguistic tricks to solve its problems is the functioning of the brain. In this case, the language consists of electric signals propagating along nerve fibres from neuron to neuron across the synaptic clefts. In this case the 'illicit jump' does not consist of changing from a purely linguistic level to something external which it describes, but rather in creating something real which did not exist previously, namely, consciousness. The problem at stake is much more complex here and our knowledge about it is less adequate. Let us notice that it is consciousness that has produced human languages and, in this way, the linguistic property, the starting point of our analysis, is not the beginning but rather the final product of the whole evolutionary process.

10. The third domain in which a 'linguistic approach' seems to be essential is the universe itself or, to be more precise, the laws of nature which constitute it or structure it. It is a commonplace to say that the laws of nature are expressed in the language of mathematics. Our textbooks on physics are full of mathematical formulae which are nothing but a certain formal

---

[2] J. V. Nossal, *Reshaping Life: Key Issues in Genetic Engineering* (Cambridge University Press, 1985), p. 14.

[3] *Le hasard and nécessité* (Éd. du Seuil, 1970), p. 182.

language (although rather seldom a *purely* formal language, i. e., one put into the form of an axiomatic system). Physicists claim that some of the formulae of this language express the laws of nature. This means that the language has its 'semantic reference', that it is an interpreted language. Very roughly speaking, the universe is its 'model'. I put the word 'model' in quotation marks because the universe is not a set of utterances and consequently it is not a model in the technical, semantic sense. In fact, logicians and philosophers of science construct such semantic models. The strategy they adopt is the following. They try to express all experimental results, relevant for a given physical theory, in the form of a catalogue of sentences reporting these results (these are called *empirical sentences*), and then compare the two languages: the theoretical language consisting essentially of mathematical formulae with the catalogue of empirical sentences. Physicists are usually not impressed by this procedure and prefer to stick to their own method of approaching the 'language of nature'.

Here we also encounter an 'illicit jump' from the empistemological order to the ontological order. After all, no mathematical formula, even if it is semantically interpreted in the most rigorous way, is a law of nature operating in the universe.

In the case of the genetic code and of the neural code, the language in question could be regarded as a 'language of nature' (the sequences of bases in DNA and electrical signals in neural fibres are products of natural evolution), and in this context how to change from syntaxis to semantics seems to be a non-trivial problem. However, as far as the laws of nature are concerned the mathematical language in which they are expressed is the language created by us. By using this language we *only describe* certain regularities occurring in the real universe, and we could clain that the problem of the mutual interaction between syntaxis and semantics is no more complicated than in our human languages.

I do think, however, that there is a subtle and deep problem here. Every property of the world can be deduced from a suitable set of laws of nature, i.e., from a suitable set of suitably interpreted mathematical formulae – all with the exception of one, the most important, namely, existence. Nowadays physicists are able to produce models of the quantum origin of the universe out of nothingness, but in doing so they must assume (most often they do so tacitly) that the laws of quantum physics exist *a priori* with respect to the universe (*a priori* in the logical sense, not necessarily in the temporal sense). Without this assumption, physicists would be unable even to start constructing their models. But somehow the universe does exist. Is

SCIENCES AND SCIENTISTS AT THE BEGINNING OF THE TWENTY-FIRST CENTURY*

PAUL GERMAIN

INTRODUCTION

Let us recall first three recent international events which show that the situation of sciences and scientists is significantly changing:

1 – *The World Conference on Science*, Budapest 26 June-1 July 1999 organised by ICSU and UNESCO. Nearly 1,800 participants from 155 countries took part.

The *Declaration on Science and the Use of Scientific Knowledge, the Agenda of Framework for Action*, and other documents were published in a special issue of *Science International*, the bulletin of ICSU (ISSN 1011-6257, September 1999, 27 pages).

The Pontifical Academy of Sciences was represented by Nicola Cabibbo, the President, Marcelo Sánchez Sorondo, the Chancellor, and myself .

2 – *The Conference of Academies*, Tokyo, May 2000, on '*Transition of Sustainability in the 21st Century*' organised by the IAP – the Inter-Academy Panel on International Issues.

A *Statement* on the subject of the conference was adopted and signed by sixty-three Academies of Sciences (including our own Academy) after a critical examination of it by these Academies.

Our colleague Peter Raven represented our Academy at this important meeting.

---

[*] This is a proposed declaration drawn up by Prof. P. Germain, Academician and Councillor of the Pontifical Academy of Sciences, which the Council of the Academy decided to publish in the Proceedings of the Jubilee Session.

3 – *Organization of cooperation between Academies of Sciences.*

During and after this Tokyo Conference, the cooperation between the Academies of Sciences was greatly reorganised.

a) The IAP

Prior to the Tokyo Conference this was a friendly association of eighty-two Academies which did not have any formal defined procedure. But, in Japan in May 2000 a provisional executive committee was elected with two co-chairs – Yves Quéré (France) and Eduardo Krieger (Brazil). The IAP Secretariat is chaired by Mohammed Hassan (TWAS) in Trieste. This committee held its first meeting in France on 6-8 July 2000. The Statutes are presently at the stage of adoption. I hope that the Pontifical Academy of Sciences will decide to apply for membership as soon as possible.

b) The IAC-Inter Academy Council

This is something like a 'working force' which will carry out studies for international organisations such as the World Bank and committees connected with UNO (the United Nations). It is chaired by two countries, and these countries at the present time are the USA and India. The Secretariat is in the Netherlands. The Board has fifteen members. One of the co-chairs of the IAP attends the meetings of the IAC Board.

These three events are very important. They show that the situation of sciences and scientists in relation to society is undergoing a major change.

The first and traditional task of the sciences and scientists remains, of course, the development of our knowledge in all the scientific disciplines. At the international level, the ICSU is the organisation which stimulates this progress and promotes the necessary cooperation.

The second task is rather new. It requires a 'New Commitment'. As was written in the 'Declaration of Science and the Use of Scientific Knowledge' of Budapest: 'The sciences should be at the service of humanity as a whole and should contribute to providing every one with a deeper understanding of nature and society, a better quality of life and a sustainable and healthy environment for present and future generations'.

For this second task, the Academies of Sciences seem ready to play an important role and this is why they have recently created new tools with which to face this new duty *together with the IAP and the IAC.*

To describe what is implied in this new task the following three lines of thought will be analysed:

I. Science as a necessary basis of technology
II. Science at the heart of culture
III. Science, a fundamental goal of education

I. SCIENCE AS A NECESSARY BASIS OF TECHNOLOGY

A dialogue between science and its application has always existed. But it has become more effective in recent decades thanks to large institutions and companies which have organised networks of scientific results and technical achievements in order to offer goods, products, possibilities, and many improvements in living conditions, in a most effective way. One such network is called a technology.

I.1 *The beneficial consequences*

We may mention just a few by way of example:

– equipment and consumer goods produced by industry;
– agricultural and food products produced by biotechnology;
– health produced by biomedical technology;
– travel and means of transport produced by the aeronautical and aerospace industries;
– instant communications produced by the telephone, television, and Internet;
– the maintenance of peace and security by the defence industries.

All these advances in technology have been very beneficial for people. Their material existence has been greatly improved. They live longer and have better health. They can enjoy a very rich cultural life.

I.2 *The current problems faced by society*

But these forms of technology have also had other consequences, which can cause serious problems to society. They are partly due to, or increased by, the main goal of companies whose chief concern is the money that their shareholders will receive. Let us briefly describe some of these problems.

– The management of non-renewable resources, for instance oil, gas, and minerals;

– the deterioration of biodiversity, in particular the diminution in the number of species (plants, insects, animals) and the areas devoted to forests;

– the deterioration of the environment due to pollution, the greenhouse effect, the increase in world temperature, and the modification of the climate;

– the exhaustion of resources brought about by population growth (food, water, energy);

– the dangers of nuclear arms or the risks of accidents in nuclear power plants;

– the social and ethical problems produced by excessively rapid technological evolution.

I.3 *The need for scientific expertise*

Governments and political authorities encounter difficulties in analysing the reasons behind these situations and in discussing what can be done to overcome them. It is a natural step to ask the scientific community to help them to understand causes and to tell them what can be done in order to avoid these negative consequences. That is precisely the role of scientific expertise.

Scientific expertise must be seen in a more positive light by the scientific community. At the present time the provision of scientific expertise is one of that community's major tasks. Publications and journals devoted to this kind of scientific work should exist. Scientific experts must be independent of the authority which asks them for expertise. They must investigate all the possibilities which are available and not report only on that which obtains the majority preference among the members of the committees of experts – committees which should be composed of scientists representative of all the various scientific disciplines.

It may happen that they recommend further research into a problem. Some of the questions which have been listed above require the constant application of expertise.

Lastly, we should strongly remind decision-makers that it is their duty to ask for expertise on matters where science and technology are competent and can consequently provide useful information.

II. SCIENCE AT THE HEART OF CULTURE

Despite the fact that the production and justification of scientific results are independent of philosophical, political, ethical, and religious considerations, the development of scientific knowledge has many cultural consequences.

II.1 *Views of the world more realistic*

– The *geocentric* view of the world was replaced by a *heliocentric* view which appeared immediately after the emergence of modern science.

– In the nineteenth century *the history of life* and of living beings was described by *evolution*.

– In the twentieth century it was discovered that the Laplacian view of the world based on *Newton's mechanics*, with its notions of absolute time and absolute space, and which was thought for more than two hundred years to be an accurate description of the world, was only a very good approximation to Albert Einstein's conception. His theories of *relativity* gave rise to perceptions of new relations between space and time, and between matter and energy.

– Progress in astrophysics led us to see that the *universe*, like life, has a *history*. It is in expansion and we have begun to investigate its billions of galaxies, stars, and planets.

– Physics discovered that matter, energy, and radiations appear to be the work of elementary particles ruled by quantum mechanics for which at this level the usual concepts of causality, locality and separability lose their relevance, and in such a way that their universal character may be questioned.

– Biology has indisputably reached the status of being a science of chemistry, with the discovery of the double helix, DNA, the genetic code, and the genome, which, indeed, has already been completely mapped.

Further demonstrations of our understanding and mastering of the world can be easily described. Let us mention two examples: the possible complexity of the behaviour of dynamic systems known as deterministic chaos which may prevent us from making long-term predictions, and the domestication of electronics which has given rise to the fantastic possibilities – which are steadily increasing – of communications.

II.2 *The temptations of a totalitarian claim*

This fantastic history has very often given rise to “ideologisation” – the belief that scientific results have a “metaphysical implication” and that they provide the only valid knowledge. This was especially the case during the nineteenth century and in particular during its last decades when many people believed that scientific development would continue to produce similar progress in the field of human and social problems.

Such a view was too optimistic. International and social problems are not solved by scientific development. On the contrary: the wars of the twentieth century were terrible as a consequence of the progress of science.

This progress has also shown that our various forms of science can build astounding models of the “real” world, but it has also shown that these are models which can always be improved. We are grateful that today we have a better understanding of what science is and what it may continue to tell us. We encounter too much disenchantment today. We still have much to learn by studying phenomena because they still have much to offer us. Yet we should not ask them things they cannot tell us.

II.3 *The role of scientific knowledge within human knowledge*

Scientific knowledge has played, and will continue to play, a very important role within human knowledge. But it cannot claim to replace or supplant other sources of knowledge. Two may be mentioned here:

– *The human, social and economic sciences.* These are more recent and have been produced by mankind through a critical analysis of facts, taking account, when possible, of the results of the natural sciences. They are concerned almost exclusively with the past and the present, and their techniques and results are often coloured by the cultural context of their authors.

– *The “humanities”.* Human thought has a long history which goes back several centuries before our present era. From thought emerged man’s knowledge and our present-day sciences. But all these sciences cannot exhaust the wealth of this thought which is the basis and the source of our perception of human dignity, our personality, in which is to be found most of our foundations and aspirations.

II.4 *Science and ethics*

Scientific activity and results have to be integrated into the culture of the society in which, and for which, the scientists are working, but without forgetting about the ethical principles of science.

– Scientific work requires freedom of thought and expression and, more generally, everything that is required by human rights.

– The ethics of science imply that every scientist obeys a code of “good behaviour” of a deontological nature.

– There is no frontier to scientific knowledge. But the scientific community must not forget that the progress of science and its application must always respect human dignity and benefit the whole of mankind, each country of the world and future generations, and work to reduce inequalities.

– Scientific expertise is often provided by committees of ethics which have to be rigorously controlled, in which scientists can use their own expertise. But in many cases, in the case of very serious problems which are of great importance for the dignity of the person, or for the future of humanity, one must prevent scientific experts from dealing with positions or questions which are the proper concern of the decision-making bodies of a democracy.

Meeting such a requirement is not easy. One can appoint a multi-disciplinary committee and add a few people working with scientists who can represent non-scientists. One can also organise debates, especially between those various schools of belief or opinion which are very concerned with the destiny of man, in such a way that they can exchange and compare their positions.

III. SCIENCE, A FUNDAMENTAL GOAL OF EDUCATION

The scientific community has always been concerned with the education of future scientists (researchers, lecturers, engineers, doctors). But in the present context of the new commitment of science and technology within society a far more important involvement in education of a broad public is of primary importance in order to make the actions which have been analysed in the two preceding sections more effective.

III.1 *A paradoxical and even dangerous situation*

Science and technology are, without any doubt, the “motor” of our rapidly changing world. The recent new developments described in section II. 1, and the new problems faced by society, are factors which bring out the truth of this statement. But at a more simple level the same may be said of the experience of daily life. People are surrounded by the products of technology which make their lives easy, interesting, and fruitful, although sometimes also tiring. Their world is largely shaped by science. Nonetheless, in most cases, they have no idea of why this is so. That is something which remains mysterious. They do not understand science and, what is even more serious, they think that they will never understand it. From this point of view, they are scientifically illiterate.

That is not a satisfactory situation. Firstly, because access to knowledge, especially to that knowledge which shapes our lives, is an important component of the human being and human dignity. Secondly, because it produces a number of people who feel that they are excluded from society. Such a feeling of exclusion must be avoided. Lastly, because it prevents the sound working of democracy. As has already been observed above, such an exercise is necessary in order for the right decisions to be taken on questions which may affect the future of humanity.

III.2 *Who will be involved in this great education project?*

The answer is simple: everybody. Children in elementary schools, teenagers in high schools, students in universities, future teachers and lecturers, and the general public as well. The idea is to promote different kinds of initiatives and experiences in order to spread knowledge about the progress and results of the world of science. In elementary schools, for example, interesting initiatives have already been taken: in the United States of America there is the “Hands On” project, in France there is “La Main à la Pate”, and similar initiatives have been promoted in China. The aim is to provide children with the opportunity to engage in a practical experience, to discover something, and to report their results. This is a complete educational exercise. It shows children what a scientific achievement is, irrespective of the position of their parents within society, their nationality, or their political ideas. In short, it tells them what scientific research really involves at a practical level.

III.3 *Who will be the actors in this project?*

Of course, in the front line, there will be scientists. Not only those who teach in departments devoted to the preparation of future teachers and lecturers, but also scientists, researchers, lecturers and engineers who could draw up new teaching methods well suited to a specific public, new paths by which to make people participate in new knowledge. But also scientists from other disciplines, from the history and philosophy of science for example, and – why not? – scholars from other branches of knowledge. One may also think of scientific journalists or experts in public communications – active in radio and TV in particular. And of course there are all the possibilities opened up by the use of the “Web”. In general, all those people who are ready to take part in this great education project form the broad scientific community, which works for the integration of the achievements of science into the culture of every society and of humanity as a whole.

Conclusion

We are living in curious times, in a contemporary world which is like a train equipped with a very powerful engine. Scientists are the engineers who have built the engine, who are most able to master it, and, consequently, who are able to master the train itself. The people sitting in the train are happy to be in it but they are also very concerned about what might happen. The duty of the scientific community is to understand their fears and their questions, and to make the journey as comfortable as possible. That, today, is the new task of this community, and one which this message has tried to analyse.

Some scientists and philosophers think that humanity is today undergoing a dramatic period which is unprecedented in history – with the exception of when our ancestors found out how to use seeds and thereby engage in agriculture or how to domesticate animals and set them to work. At that time it was impossible to foresee what would happen in the future. At the beginning of the third millennium are we not perhaps in a similar situation?

We may also bring to mind that wonderful work of science-fiction by Aldous Huxley, ”Brave New World”, which was published in 1932. Are we now entering this new world?

STUDY-DOCUMENT ON THE USE OF ‘GENETICALLY MODIFIED FOOD PLANTS’ TO COMBAT HUNGER IN THE WORLD

I. INTRODUCTORY NOTE BY PRESIDENT NICOLA CABIBBO

During the closed session of the Academy held during the Plenary Session many Academicians expressed deep concern at the distorted way in which recent scientific results, and in particular those relating to genetically improved plant varieties, have been presented to the public. It was decided to establish a committee with the task of producing a document on this subject. The chairman of the committee was A. Rich and its other members were W. Arber, T-T. Chang, M.G.K. Menon, C. Pavan, M.F. Perutz, F. Press, P.H. Raven, and R. Vicuña. The document was examined by the Council at its meeting of 25 February 2001, submitted to the members of the Academy for their comments, and then sent to the committee for the preparation of the final version.

The document, which is included in the Proceedings, expresses the concerns of the scientific community about the sustainability of present agricultural practices and the certainty that new techniques will be effective. At the same time, it stresses the need for the utmost care in the assessment and evaluation of the consequences of each possible modification, and on this point we cannot but recall the exhortation of John Paul II regarding biotechnologies made in his speech of 11 November 2000 on the occasion of the Jubilee of the Agricultural World: ‘they must be previously subjected to rigorous scientific and ethical control to ensure that they do not give rise to disasters for the health of man and the future of the earth’.

The document also expresses concern about excesses with regard to the establishment of ‘intellectual property’ rights in relation to widely used crops – excesses which could be detrimental to the interests of developing nations.

A further recommendation, clearly stated in the document, is that the examination of the safety of newly developed cultivars should be based on well-documented methods and that the methods and results should be openly discussed and scrutinised by the scientific community.

The Academy will devote an *ad hoc* meeting to the subject of genetically modified food plants. This meeting will provide an opportunity to examine in depth many issues which are raised in the document and which are of special concern: the methods used in the testing and licensing of the new cultivars; the comparative risks associated with different methods of pest control; and the many scientific, ethical and social issues raised by the introduction of a new and powerful technology directed towards agricultural improvement.

II. RECOMMENDATIONS

The Challenge

1. The rapid growth of the world population requires the development of new technologies to feed people adequately; even now, an eighth of the world's people go to bed hungry. The genetic modification of food plants can help meet part of this challenge.

2. Agriculture as it is currently practiced is unsustainable, as is indicated by the massive losses of topsoil and agricultural land that have occurred over the past few decades, as well as by the unacceptable consequences of massive applications of pesticides and herbicides throughout most of the world. Techniques to genetically modify crop plants can make important contributions to the solution of this common problem.

The Potential of Genetically Modified Food Plants

3. Virtually, all food plants have been genetically modified in the past; such a modification is, therefore, a very common procedure.

4. The cellular machinery of all living organisms is similar, and the mixing of genetic material from different sources within one organism has been an important part of the evolutionary process.

5. In recent years, a new technology has been developed for making more precise and specific improvements in strains of agricultural plants, involving small, site-directed alterations in the genome sequence or sometimes the transfer of specific genes from one organism to another.

6. Genetically modified food plants can play an important role in improving nutrition and agricultural products, especially in the developing world.

Conditions for the Beneficial Use of this New Technology

7. The scientific community should be responsible for the scientific and technological research leading to the advances described above, but it must also monitor the way it is applied and help ensure that it works to the effective benefit of people.

8. There is nothing intrinsic about genetic modification that would cause food products to be unsafe. Nevertheless, science and scientists are - and should further be – employed to test the new strains of plants to determine whether they are safe for people and the environment, especially considering that current advances can now induce more rapid changes than was the case in the past.

9. The methods used for testing the safety of new genetically modified strains (or more precisely, cultivars) of plants should be publicly available, as should the results of these tests, in both the private and public sectors.

10. Governments should have the responsibility for ensuring that the tests and their results are conducted in line with the highest criteria of validity. The protocols of evaluation should be made widely accessible.

11. Governments should increase their funding for public research in agriculture in order to facilitate the development of sustainable and productive agricultural systems available to everyone.

12. Intellectual property rights should not inhibit a wide access to beneficial applications of scientific knowledge. In the development of this modern genetic technology for agriculture, efforts should be made to facilitate cooperation between the public and private sectors and to secure the promotion of solidarity between the industrialised and developing worlds.

13. Special efforts should be made to provide poor farmers in the developing world with access to improved crop plants and to encourage and finance research in developing countries. At the same time, means should be found to create incentives for the production of vegetable strains suitable to the needs of developing countries.

14. Research to develop such improvements should pay particular attention to local needs and to the capacity of each country to engage in a necessary adaptation of its traditions, social heritage, and administrative practices in order to achieve the success of the introduction of genetically modified food plants.

Recommendation for the Scientific Community

15. In order to help governments, state-funded researchers, and private companies to meet the above conditions, and in order to facilitate the development of common standards and approaches to this problem in both developing and industrialised countries, the scientific community, represented by its established worldwide umbrella organisations, should offer its expertise. A suitably composed international scientific advisory committee could be entrusted with this all-important task.

III. BACKGROUND

The Pontifical Academy of Sciences has traditionally stressed the application of science to world food problems. Most recently, the study week proceedings on "Food Needs of the Developing World in the Early Twenty-First Century" and "Science for Survival and Social Development," two conferences held in 1999, emphasized the special role of modern biotechnology in improving the characteristics of plants. Here, the members of the Pontifical Academy are considering newer aspects of these applications in a global context.

The world's people have grown in number from 2.5 billion to more than 6 billion over the past fifty years. One out of four lives in extreme poverty, and one out of eight is chronically malnourished. These problems are in part related to patterns of distribution of the available food, in part to the low productivity of agriculture in certain regions, including the loss of crops to pests, and in another part to an unbalanced nutritional value in the daily diet. Enhanced production of qualitatively improved food under sustainable conditions could greatly alleviate both poverty and malnutrition. These are goals that will become even more urgent as our numbers increase by an estimated two billion additional people over the next few decades. Modern science can help meet this challenge if it is applied in an appropriately constructive social and economic context.

Historical Use of GM Plants

Genetically modified (GM) plants can play an important role in alleviating world food problems. Recent discussions concerning GM plants have often overlooked the fact that virtually all commonly used foods have been genetically modified, often extensively, during the long history of agriculture. Ever since the start of agriculture about 10,000 years ago, farmers have selected plant variants that arose spontaneously when they offered increased productivity or other advantages. Over time, new methods for producing desirable genetic variants were introduced, and have been used extensively for some two centuries. Cross-breeding of different plant varieties and species, followed by the selection of strains with favorable characteristics, has a long history. That process involves exchanging the genetic material, DNA, from one organism to another. DNA contains genes, and genes generally act by expressing proteins; thus the newly modified plant obtained by genetic crossing usually contains some proteins that are different from those in the original plant. The classical method of crossing plants to bring in new genes often results in bringing in undesirable genes as well as desirable ones since the process could not be controlled.

New Technology to Develop GM Plants

Almost 30 years ago scientists developed a new technology called recombinant DNA that made it possible to select the particular gene that one wanted to transfer to a plant. This process is very specific and avoids the inclusion of genes that are undesirable. A number of useful new plant strains have been developed in this way. Even though such strains are considered to be genetically modified (GM), the same label could be applied equally appropriately to all strains that have been modified genetically by human activities — a process that owes its success to selection for desirable properties.

We now know a great deal about the DNA in organisms. It contains the codes for manufacturing different proteins. At the molecular level, the products of genes, usually proteins, are made from the same materials in plants, animals and microorganisms. The recent development of technical means for sequencing the components in DNA gives us insight into the similarities among organisms. All living organisms share genes because of their common evolutionary descent. For example, the sequence of a small worm was completed recently, and it was found that the worm shares some 7,000 of its estimated 17,000 genes with humans.[1] Likewise, the genes found in microorganisms are often very similar to those found in humans as well as in plants.[2]

---

[1] The C. elegans Sequencing Consortium, 1998. 'Genome Sequence of the Nematode C. elegans: A Platform for Investigating Biology'. *Science* 282: 2012-18.

[2] The Arabidopsis Genome Initiative. 2000. Analysis of the Genome Sequence of the Flowering Plant *Arabidopsis thaliana. Nature* 408:796-815.

A large number of genes in all placental mammals are essentially the same, and about a third of the estimated 30,000 genes in humans are common to plants, so that many genes are shared among all living organisms.

Remarkably, one has discovered another reason for the similarities between DNA sequences in different organisms: DNA can at times move in small blocks from one organism to another, a process that is called lateral transfer. This occurs at a relatively high rate in microorganisms, and it also occurs in plants and animals, albeit less frequently. Once this has taken place, the genetic material that has been transferred becomes an integral part of the genome of the recipient organism. The recent sequence of the human genome revealed that over 200 of our estimated 30,000 genes came from microorganisms,[3] demonstrating that such movements are a regular part of the evolutionary process.

The new technology has changed the way we modify food plants, so that we can generate improved strains more precisely and efficiently than was possible earlier. The genes being transferred express proteins that are natural, not man-made. The changes made alter an insignificantly small proportion of the total number of genes in the host plant. For example, one gene may be introduced into a plant that has 30,000 genes; in contrast, classical cross-breeding methods often generated very large, unidentified changes in the selected strains.

Many of the statements made here in abbreviated form have been dealt with more thoroughly in a number of publications. Among the more significant is a report entitled "Transgenic Plants and World Agriculture", which was prepared by a committee representing the academies of sciences of Brazil, China, India, Mexico, the U.K. the U.S, and the Third World Academy of Sciences. In summary, it reached the conclusion that foods produced from genetically modified plants were generally safe, that any new strains needed to be tested and that further investigation of the potential ecological problems associated with such new strains also needed further consideration. The French Academy of Science also issued a very useful report, commenting on many aspects of this issue and dealing especially with the problems of deployment of GM plants in developing countries. The accumulating literature in this field has become quite extensive.

Traditional methods have been used to produce plants that manufacture their own pesticides, and thus are protected from pests or diseases.

---

[3] Venter, J. Craig *et al.* 2001. 'The Sequence of the Human Genome'. *Science* 291:1304-51.

They have also been employed to produce herbicide-resistant plants. When such plants are grown, specific herbicides are used to efficiently control the weeds growing among them without harming the basic crop. Another goal of traditional agriculture has been the nutritional enhancement of foods, either in terms of amino acid balance or in enhancing the presence of vitamins or their precursors. All of these goals can be attained more efficiently and precisely with the use of methods that are now available involving the direct transfer of genes. Newer goals, mostly unattainable earlier, include the development of plant strains that can manufacture desired substances, including vaccines or other drugs.

How to Make Sure GM Plant Products are Safe

These goals are highly desirable, but the questions that have arisen often concern the method of genetic modification itself, not its products. The appearance of these products has generated a legitimate desire to evaluate carefully their safety for consumption by human beings and animals, as well as their potential effects on the environment. As is usual for complicated questions, there are no simple answers, and many elements need careful consideration.

Contrary to common perception, there is nothing intrinsic to the genetic modification of plants that causes products derived from them to be unsafe. The products of gene alteration, just like the products of any modification, need to be considered in their own right and individually tested to see if they are safe or not. The public needs to have free access to the methods and results of such tests, which should be conducted not only by companies that develop the genetically altered plants, but also by governments and other disinterested parties. Overall, widely accepted testing protocols need to be developed in such a way that their results can be understood and can be used as a basis for consumer information.

One of the present concerns is that new genetically modified plants may include allergens that will make them unhealthy for some people. It is possible to test these plants to determine whether they have allergens. Many of our present foodstuffs, such as peanuts or shellfish, have such allergens, and they represent a public health hazard to that part of the population with corresponding allergies. It is important that any genetically modified crop varieties, as well as others produced by traditional breeding methods, be tested for safety before they are introduced into the food supply. In this connection, we also note that the new technologies offer ready methods for removing genes associated with allergens, both in present crops and newly produced ones.

Another issue concerns the potential impact of genetically modified plants on the environment. Cultivated plants regularly hybridize with their wild and weedy relatives, and the exchange of genes between them is an important factor in plant evolution. When crops are grown near relatives with which they can produce fertile hybrids, as in the case of maize and its wild progenitor teosinte in Mexico and Central America, genes from the crops can spread to the wild populations. When this occurs, the effects of these genes on the performance of the weeds or wild plants needs to be evaluated. There is nothing wrong or unnatural about the movement of genes between plant species. However, the effects of such movement on the characteristics of each plant species may vary greatly. There are no general reasons why we should fear such gene introductions, but in each case, scientific evaluation is needed. The results should be verified by the appropriate government agency or agencies, and full disclosure of the results of this process should be made to the public.

Improved Foods

There are many opportunities to use this new technology to improve not only the quantity of food produced but also its quality. This is illustrated most clearly in the recent development of what is called "golden rice",[4] a genetically modified rice that has incorporated in it the genes needed to create a precursor of Vitamin A. Vitamin A deficiency affects 400 million people,[5] and it often leads to blindness and increased disease susceptibility. Use of this modified rice and strains developed with similar technologies will ultimately make it possible to help overcome Vitamin A deficiency. "Golden rice" was developed by European scientists, funded largely by the Rockefeller Foundation and using some methods developed by a private company. However, that company has agreed to make the patents used in the production of this strain freely available to users throughout the world. When successfully bred into various local rice strains and expressed at high enough levels, it offers the possibility of helping to alleviate an important nutritional deficiency. This is just one of several plant modifications that has the potential for producing healthier food.

[4] Potrykus, Ingo. 2001. 'Golden Rice and Beyond'. *Plant Physiology* 125: 1157-61.

[5] Ye, Xudong *et al.* 2000. 'Engineering the Provitamin A (b-Carotene) Biosynthetic Pathway into (Carotenoid-Free) Rice Endosperm'. *Science* 287: 303-5.

More Government-sponsored Research is Needed

Research involving the use of recombinant DNA technology to develop genetically modified plants is carried out worldwide. It involves government laboratories, independent institutes and private corporations. During the period following World War II, most international crop research was funded by the public sector and through charitable foundations. This led to a spectacular doubling or tripling of crop yields in large parts of Asia and Latin America. This “Green Revolution” met the needs of millions of poor farmers and consumers and alleviated starvation for tens of millions of people. The revolution was a consequence of the production of “dwarf” wheat and rice plants by the introduction of genes from dwarf varieties into high-yielding strains of grain. Substantial public sector agricultural research still exists in North America, Australia, Europe, China, India, Brazil and in the Consultative Group for International Agricultural Research which comprises 16 international research centers. In recent decades, however, public funding for agricultural research has dwindled, while funding from corporations has increased markedly. Governments should recognize that there is an important public interest element in this research, even in market-driven economies. Public contributions are important because the results of such research work are made available to everyone. At the same time it makes possible various opportunities for public and private collaboration, so that the benefits of the new technologies for genetic modification are brought to all of the people throughout the world. It is also important that such research not be inhibited by over-protective intellectual property measures.

Special Needs of Poor Farmers

A significant distinction must be made between the use of genetically modified plants in the developed world and their use in the developing world. In the developed world, farmers can often afford to pay for expensive seeds that yield disease-resistant crops that require lower levels of pesticides or that produce more food per hectare. This is also true for many farmers in the developing world. For poor farmers in the developing world, however, governments must intervene if they are to be able to obtain the benefits of modern crop improvement technology. Several private corporations engaged in agricultural research have indicated their willingness to make available the results of their research without charge for use in developing countries. Their willingness should be recognized and encouraged.

In this connection, we endorse the recommendation of the seven-academy group mentioned above that an international advisory committee should be established to assess the implications of genetically modified plants, especially in developing countries. The committee would identify areas of common interest and opportunity between institutions in the private and public sectors. This could be one way of assuring that the benefits of these new technologies are made widely available. Intellectual property issues are of special importance in this context. We recommend that this committee participate in the development of generally accepted standards for testing and approval of new plant strains and the foods derived from them, a development of great importance for world commerce.

The Crisis in Agriculture

The loss of a quarter of the world's topsoil over the past fifty years, coupled with the loss of a fifth of the agricultural land that was cultivated in 1950,[6] indicates clearly that contemporary agriculture is not sustainable. To become sustainable, agriculture will need to adopt new methods suitable for particular situations around the world. These include greatly improved management of fertilizers and other chemical applications to crops, integrated pest management to include improved maintenance of populations of beneficial insects and birds to control pests, and the careful management of the world's water resources. (Human beings currently use 55% of the renewable supplies of fresh water, mostly for agriculture.) It will also be necessary to develop strains of crop plants with improved characteristics to make them suitable for use in the many diverse biological, environmental, cultural and economic areas of the world.

Genetically modified plants can be an important component of efforts to improve yields on farms otherwise marginal because of limiting conditions such as water shortages, poor soil, and plant pests. To realize these benefits, however, the advantages of this rapidly growing technology must be explained clearly to the public throughout the world. Also, results of the appropriate tests and verifications should be presented to the public in a transparent, easily understood way.

[6] Norse, D. *et al.* 1992. 'Agriculture, Land Use and Degradation'. pp. 79-89. In Dooge, J.C.I. *et al.* (eds.). *An Agenda of Science for Environment and Development into the 21st Century*. Cambridge University Press, Cambridge.

An estimated 85 million birds and billions of insects[7] are killed annually in the United States alone, as a result of the application of pesticides on crops. Some 130,000 people become ill in this connection each year. Genetically modified plants currently in use have already greatly reduced the use of such chemicals, with great ecological benefits. It is expected that such benefits will be significantly enhanced as research and development efforts continue.

Hope for the Future

Finally, it is important that scientists make an effort to clearly explain to the public the issues concerning risk. All technological developments have elements of risk, whether we refer to the introduction of vaccines, new forms of therapy, new types of foodstuffs or new pesticides. Risk cannot be avoided, but it can be minimized. The long-term aim is to develop plants that can produce larger yields of healthier food under sustainable conditions with an acceptable level of risk. The latter can be determined by scientific studies, with the results made freely available to the public.

The developments we have discussed here constitute an important part of human innovation, and they clearly offer substantial benefits for the improvement of the human condition worldwide. They are essential elements in the development of sustainable agricultural systems capable of feeding not only the eighth of the world's population that is now hungry, but also meeting the future needs of the growing world population. To make the best use of these new technologies and the agricultural management opportunities they create is a moral challenge for scientists and governments throughout the world.

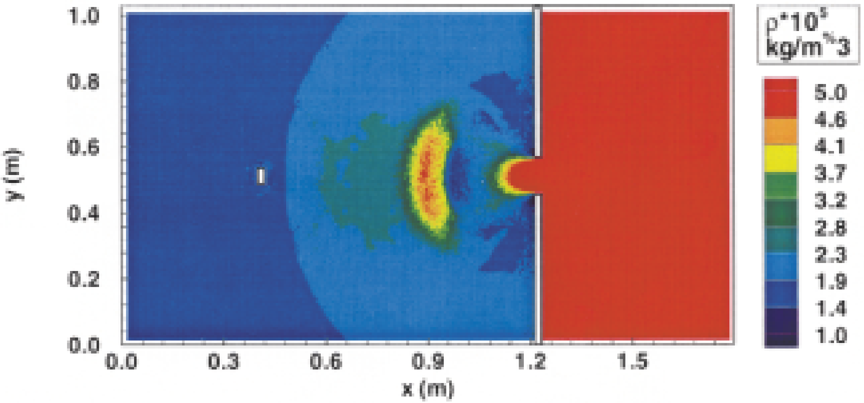
---

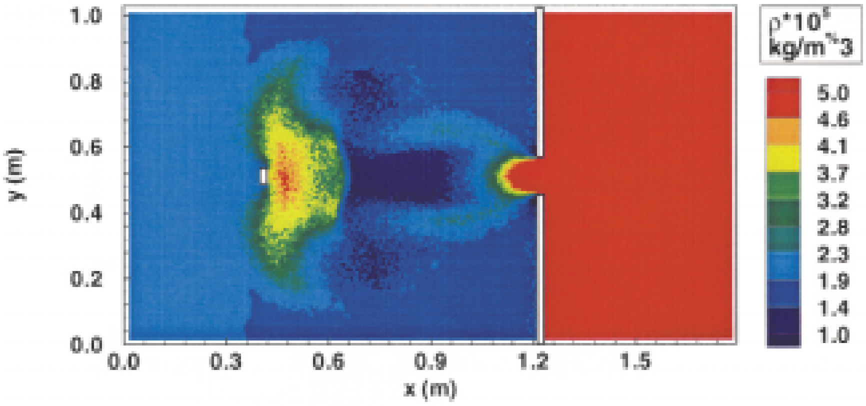
[7] Pimentel, D. *et al.* 1992. 'Environmental and Economic Costs of Pesticide Use'. *BioScience* 42: 750-59.

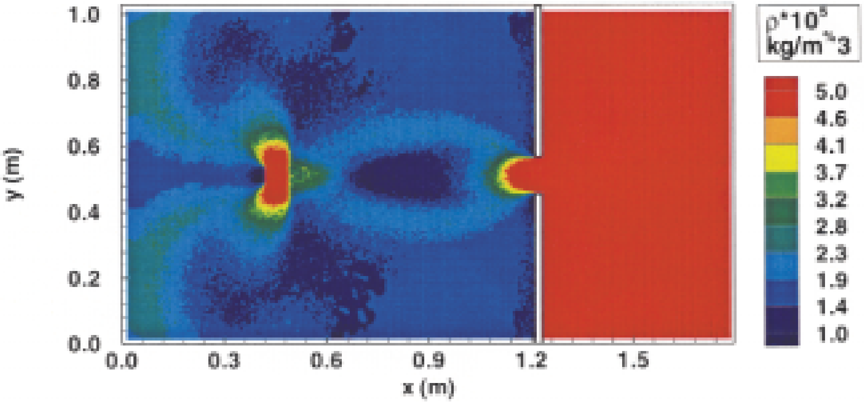
there here a similar ‘illicit jump’ as in the case of the genetic and neural codes? If so, this ‘illicit jump’ would be no more and no less than the mystery of creation itself.

11. We would fall victim to a facile temptation if we treated the above considered ‘illicit jumps’ as gaps in the structure of the universe which could be (or even should be) filled in with the ‘hypothesis of God’. The true duty of science is never to stop asking questions, and never to abandon looking for purely scientific answers to them. In my view what seems to be an ‘illicit jump’ from the point of view of our present logic is in fact nature’s fundamental strategy in solving its most important problems (such as the origin of life and consciousness). The limitations of our logic are too well known to be repeated here (Gödel’s theorems, problems with applications of the standard logic to quantum theory, etc.). My hypothesis is that our ‘Aristotelian logic’ is too simplistic to cope with the problems we are considering at this conference. What we need is not another ‘non-standard’ logical system which is constructed by changing or rejecting this or that axiom or this or that inference rule. What we need is something radically new: a far-reaching revolution comparable with that in changing from linear physics to non-linear physics.

I do not think that we would have any chance of inventing such a logic by experimenting with purely symbolic operations and having it at our disposal to successfully apply it to solving the problem of life and consciousness. On the contrary, such a logic will probably emerge from the analysis of concrete empirical investigations, and will constitute only one component of the solution of the problem.


1.0
0.8
0.6
0.4
0.2
0.0
y (m)
0.0
0.3
0.6
0.9
1.2
1.5
x (m)
ρ*10^5 kg/m**3
5.0
4.6
4.1
3.7
3.2
2.8
2.3
1.9
1.4
1.0


1.0
0.8
0.6
0.4
0.2
0.0
y (m)
0.0
0.3
0.6
0.9
1.2
1.5
x (m)
ρ*10^5 kg/m**3
5.0
4.6
4.1
3.7
3.2
2.8
2.3
1.9
1.4
1.0


1.0
0.8
0.6
0.4
0.2
0.0
y (m)
0.0
0.3
0.6
0.9
1.2
1.5
x (m)
ρ*10^5 kg/m**3
5.0
4.6
4.1
3.7
3.2
2.8
2.3
1.9
1.4
1.0

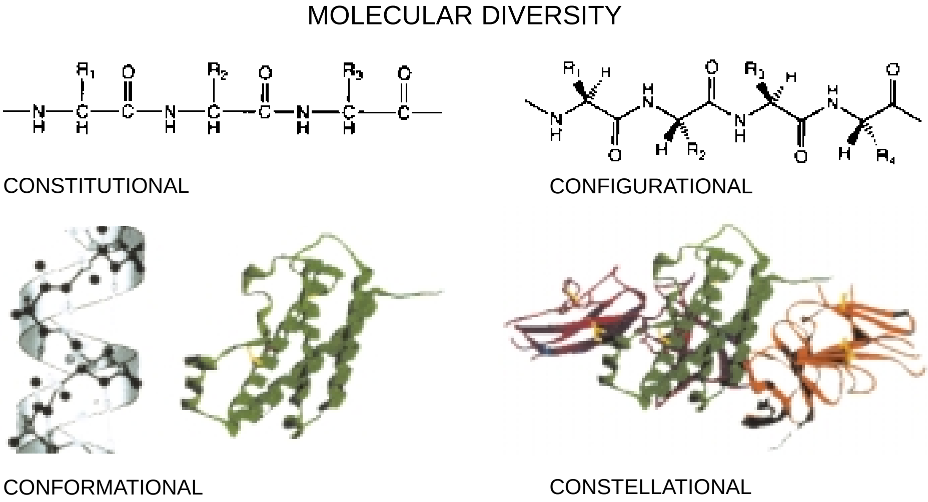


Fig. 5. Four levels of describing the structure of biomolecules: Proteins.

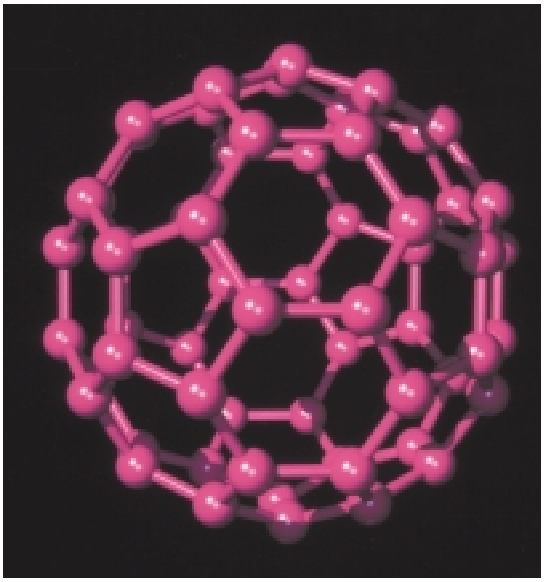
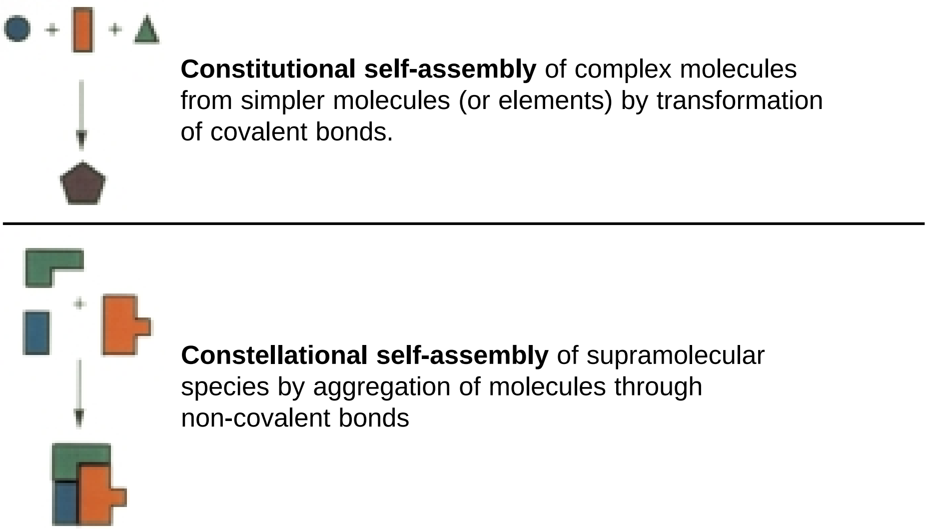


Fig. 7. Buckminsterfullerene. A complex molecule that can assemble itself (courtesy Prof. F. Diederich, ETH).



Constitutional self-assembly of complex molecules from simpler molecules (or elements) by transformation of covalent bonds.

Constellational self-assembly of supramolecular species by aggregation of molecules through non-covalent bonds

Fig. 8. Self-assembly of molecules and self-assembly of supramolecules.

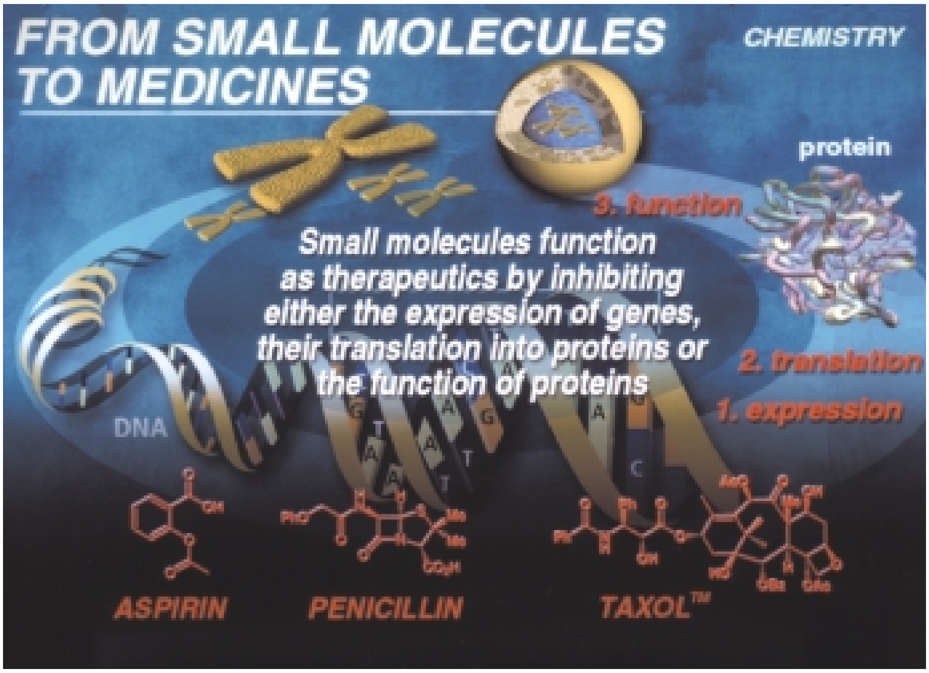
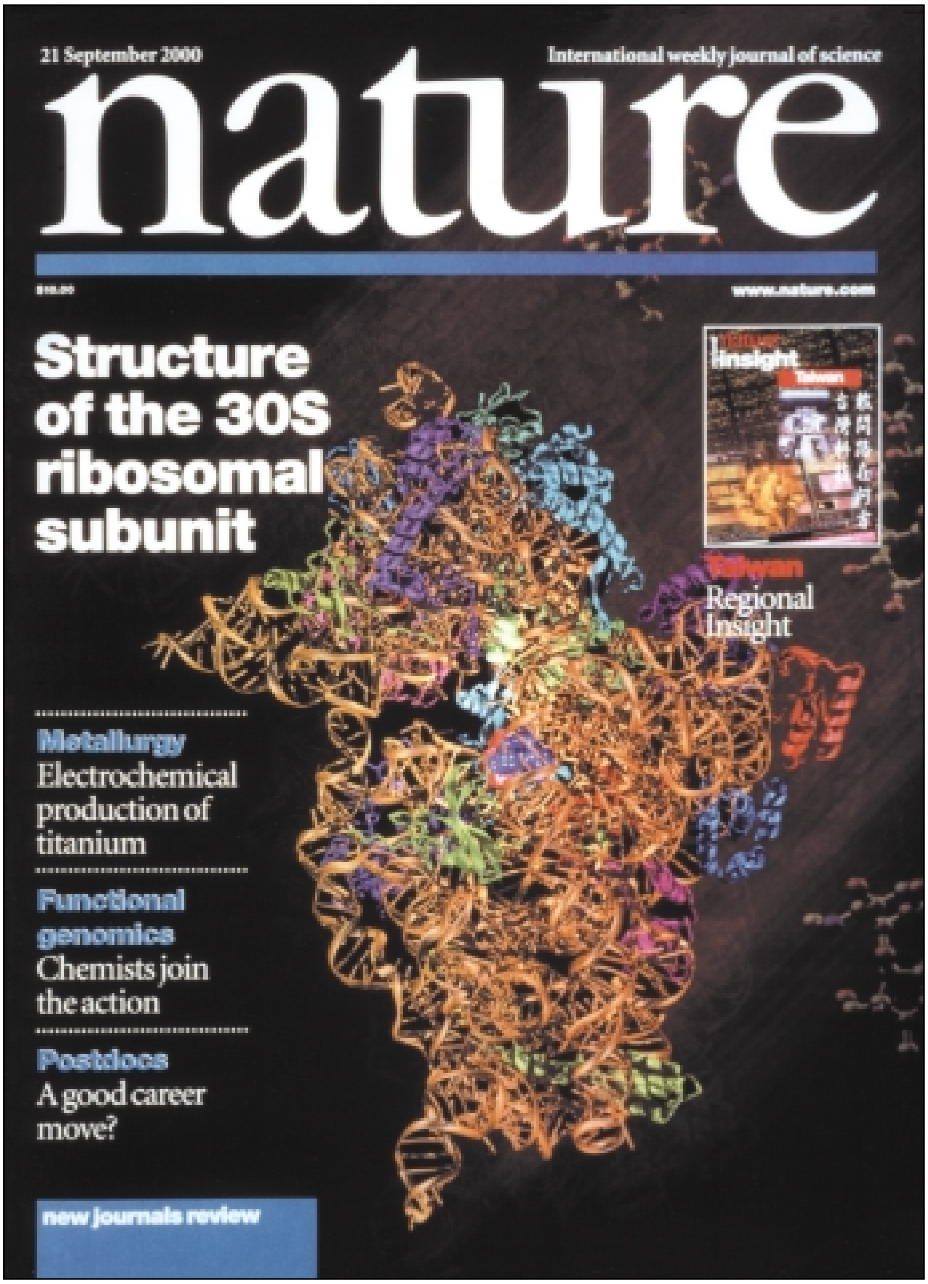


Fig. 10. Medicinal natural products chemistry (courtesy of Prof. K. C. Nicolaou, TSRI).



21 September 2000

International weekly journal of science

nature

www.nature.com

Structure of the 30S ribosomal subunit

Taiwan

Regional Insight

Metallurgy

Electrochemical production of titanium

Functional genomics

Chemists join the action

Postdocs

A good career move?

new journals review

Fig. 9. The structure of the Ribosome: a landmark in biological chemistry.

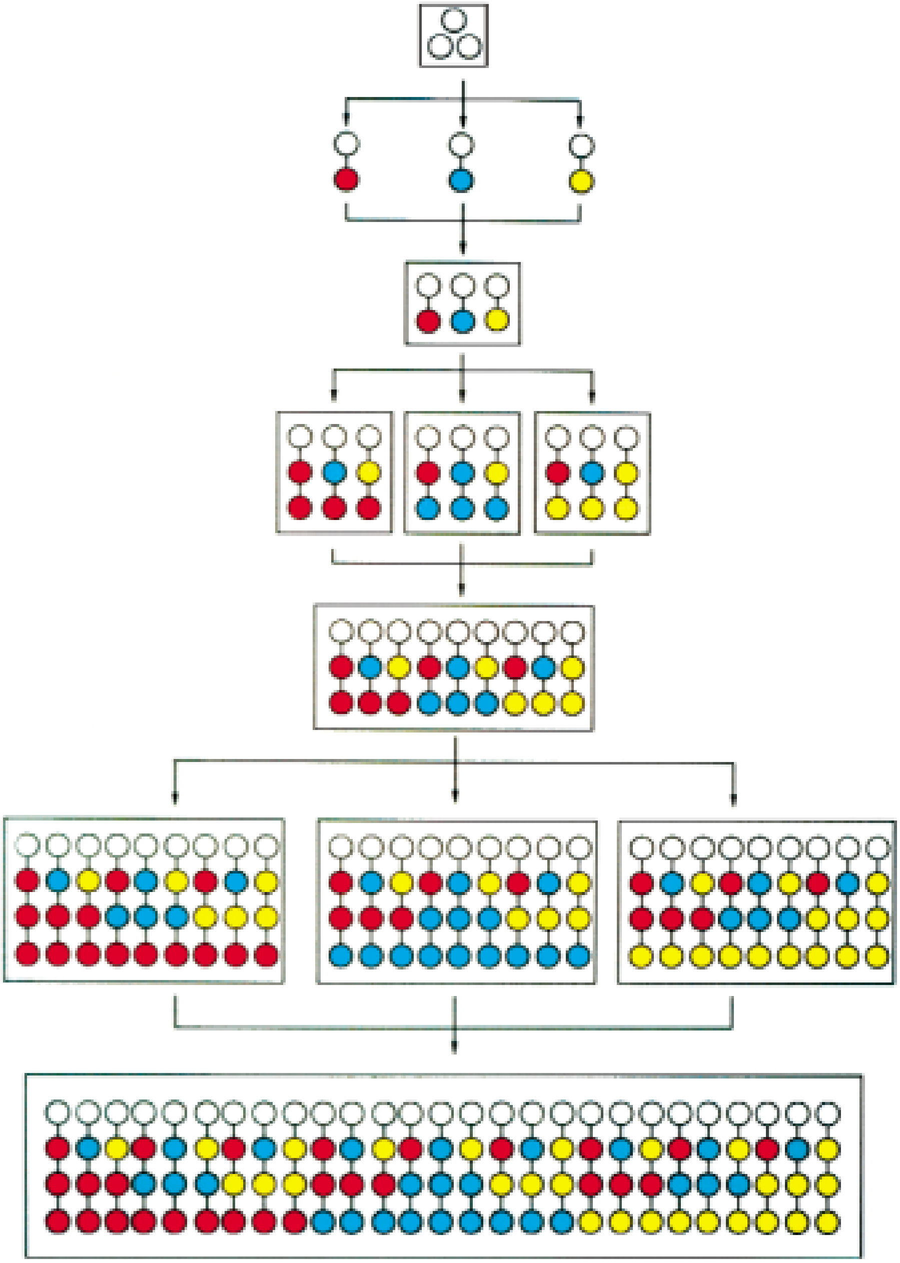


Fig. 12. The principle of combinatorial synthesis illustrated (courtesy of Prof. G. Quinkert, Frankfurt).

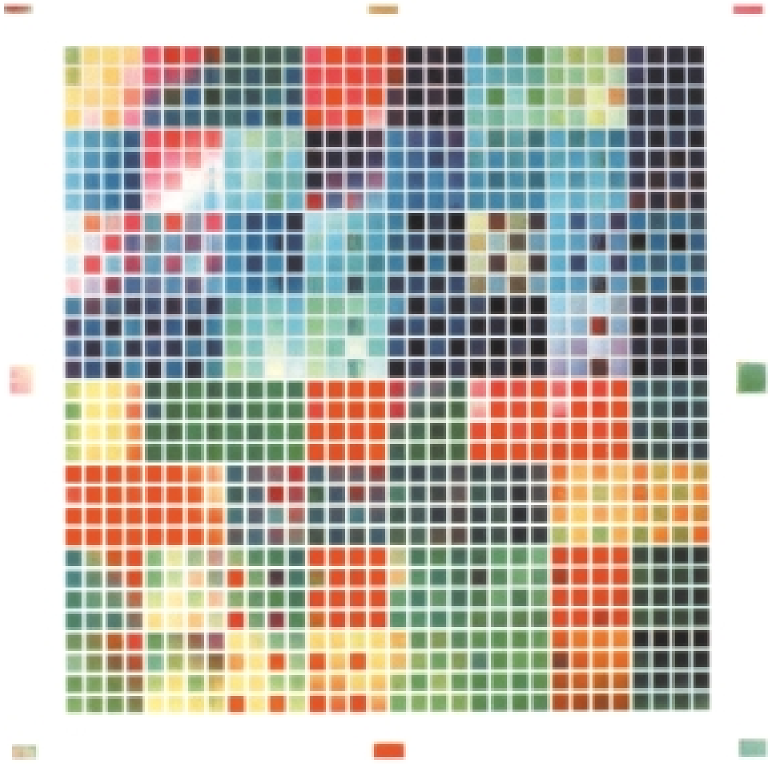


Fig. 14. Materials science: combinatorial search for catalysts (courtesy of Prof. P. Schultz, La Jolla).

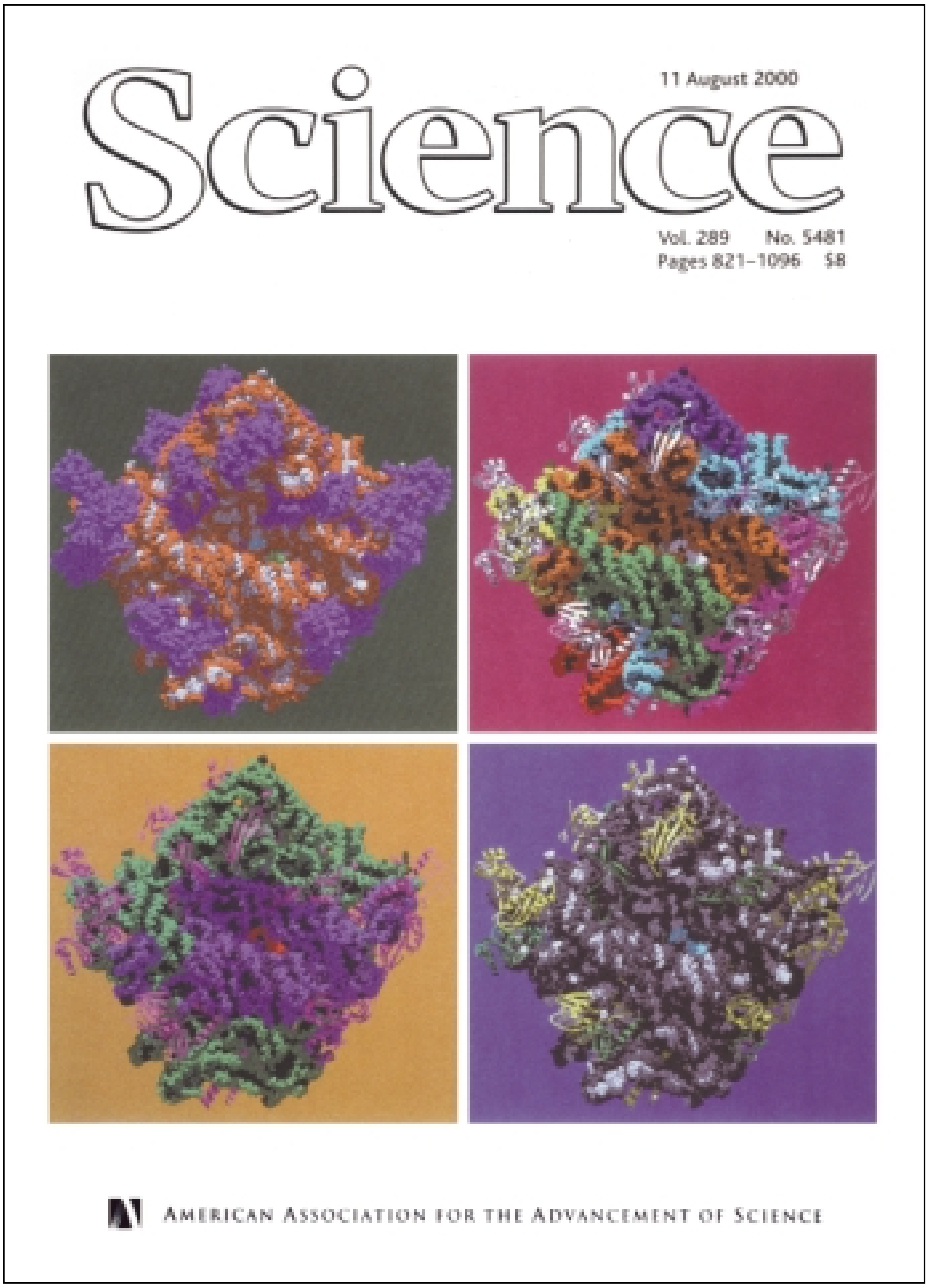


Fig. 15. The ribosome again.

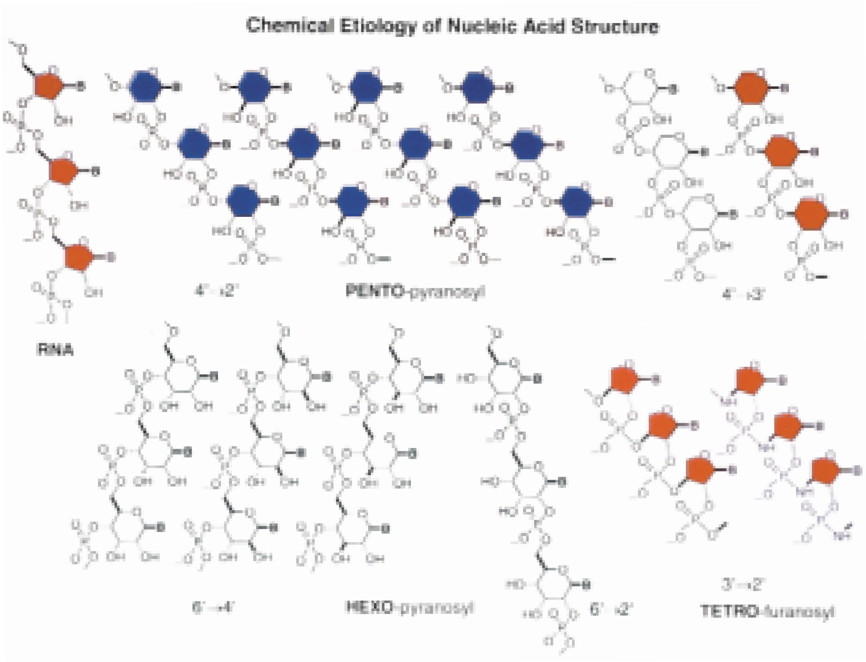


Fig. 17. Potentially natural nucleic acid alternatives studied experimentally so far.

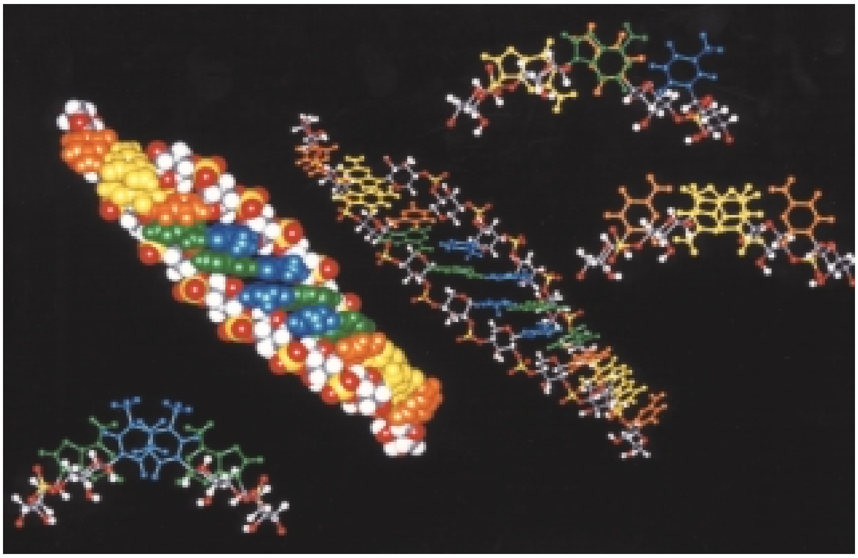


Fig. 18. Pyranosyl-RNA, an example of an alternative nucleic acid that shows stronger Watson-Crick pairing that RNA itself (NMR-structure).

Fig. 2.

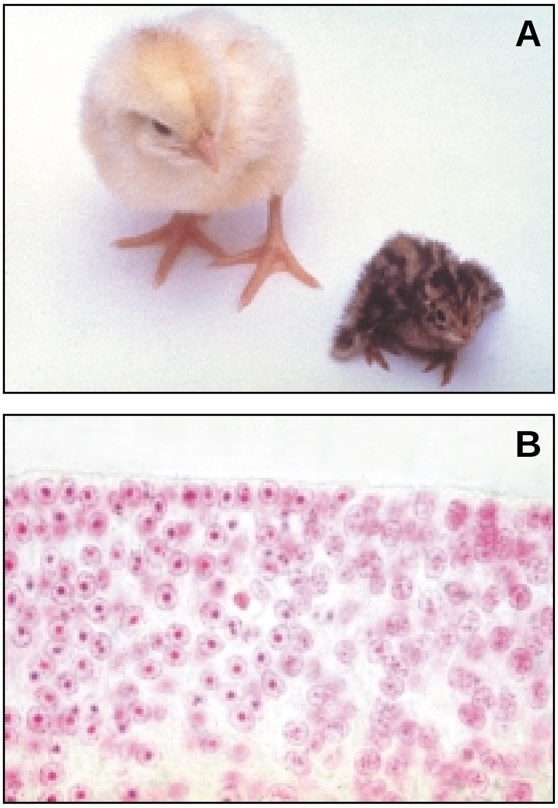


Fig. 3.

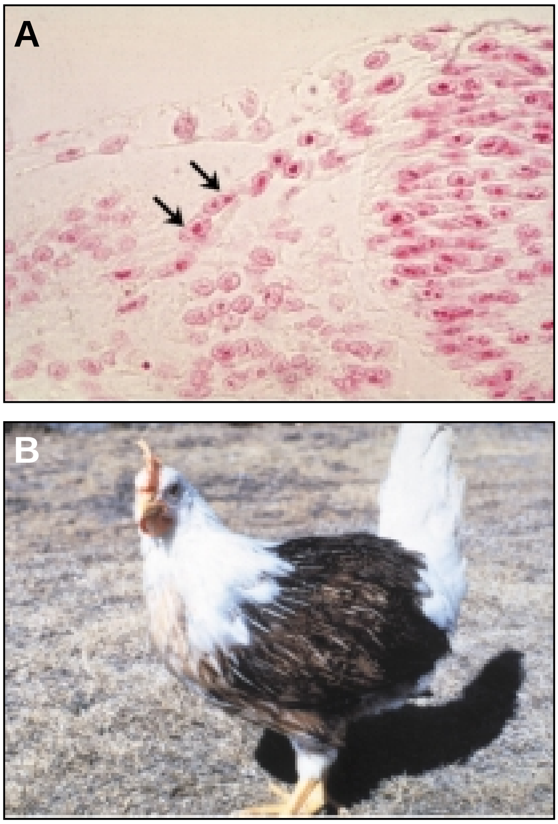


Fig. 5.

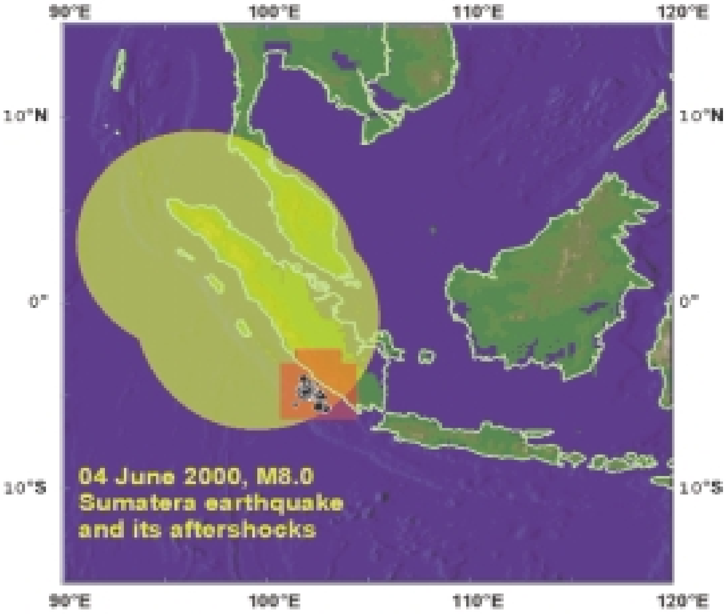


Figure 5. Successful advance prediction of the Southern Sumatera earthquake (4 June 2000, magnitude Ms = 8.0). The alarm areas in the first (M8 algorithm) and the second (MSc algorithm) approximations are highlighted by yellow and red respectively. [From the web site: http://www.mitp.ru].

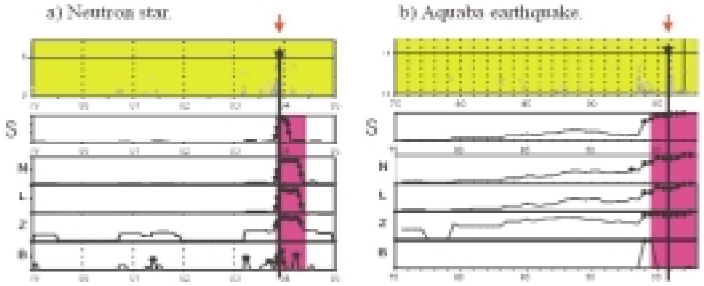


Figure 7. Similarity of premonitory seismicity patterns in Aquaba gulf (panel b) and on neutron star (panel a). Top - sequence of events. Major ones are shown by a star: Aquaba earthquake, 1995, energy ~ 10^{23} erg and the starquake recorded in 1983, energy ~ 10^{41} erg. Other boxes show premonitory patterns used in earthquake prediction. *S* depicts the change in energy distribution, *N* – the rate of earthquake occurrence, *L* – its deviation from long term trend, *Z* – concentration of events in space, *B* – clustering in space and time. Dots show the values, exceeding a standard threshold. [After Kossobokov *et al.* 2000].

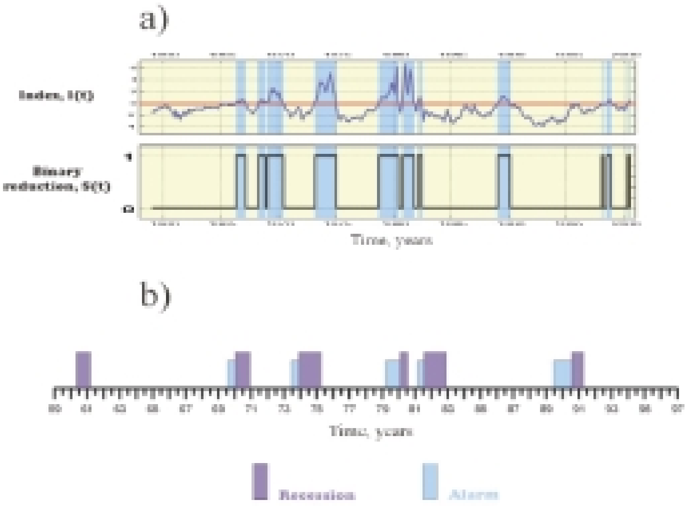


Figure 8. Prediction of US recession by premonitory patterns of 6 macroeconomic indicators. a) Each index *I(t)* is replaced by its binary representation *S(t)*. Here *I(t)* is the difference between the interest rate on short-term and long-term bonds. When $I(t)>0$ $S(t)=1$ (typical before recessions). When $I(t)<0$, $S(t)=0$. b) Performance of hypothetical prediction algorithm: an alarm is declared for 9 months when 4 or more indicators signal approach of a recession.

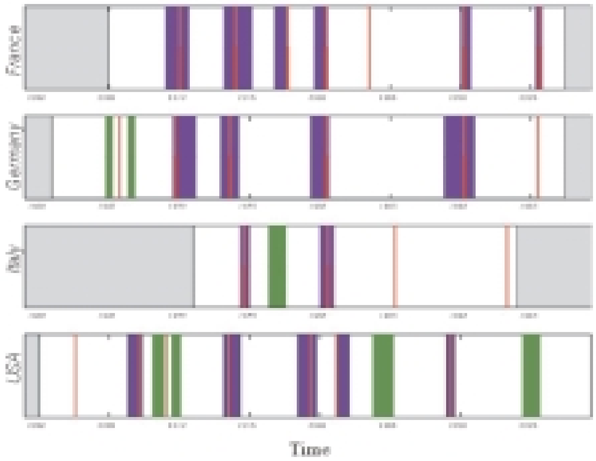
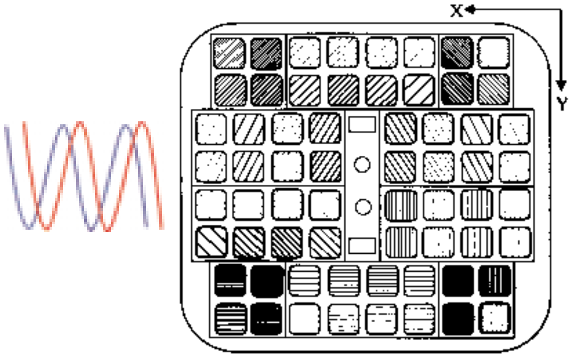
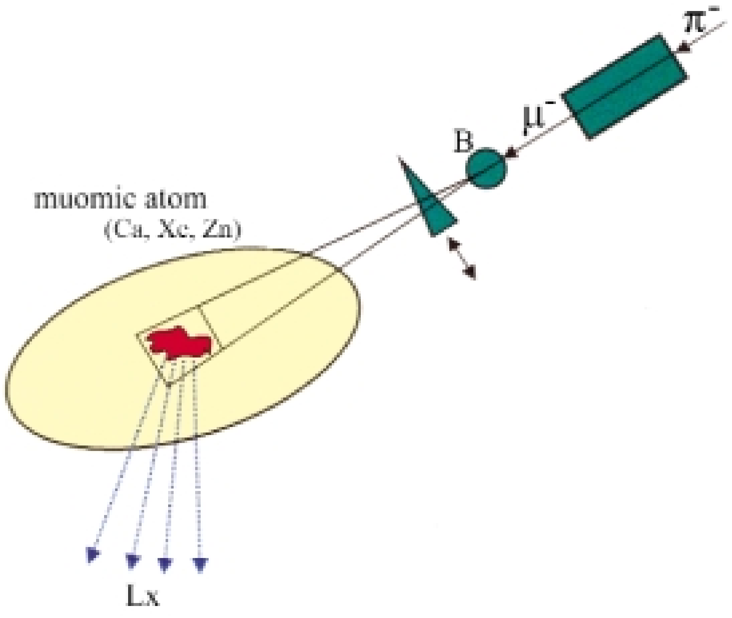


Figure 9. Prediction of fast acceleration of unemployment (*FAU*). Precursor is the steep rise of three national macroeconomic indicators. Red vertical lines – moments of FAU. Blue bars – periods of alarms. Green bars – false alarms. Gray areas on both sides – periods, for which the economic indicators were unavailable.



Grid for the Fourier Transform Telescope (FTT)

fig. 2



Muonic atoms produced by the muon beam

Fig. 4

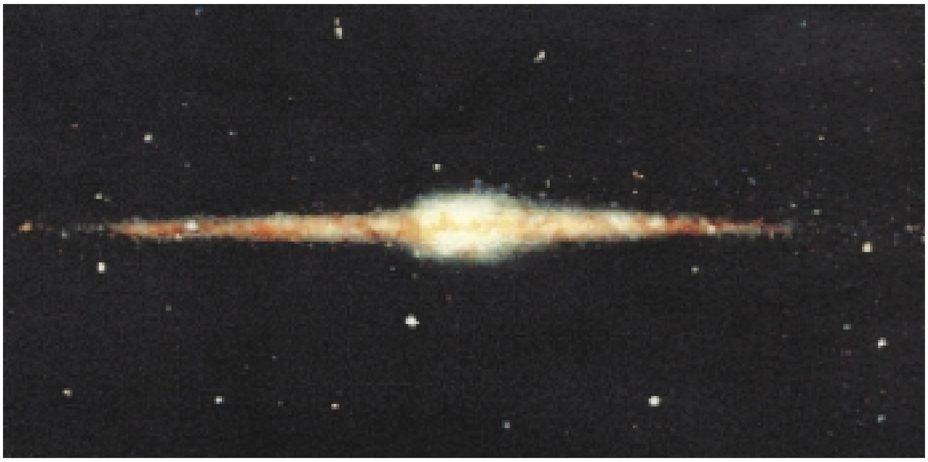


Figure 1. A near-infrared image of the Milky Way showing the central bulge and about 190 degrees of the galactic plane, taken by the COBE orbiting satellite. Most of the light in the disk and bulge comes from stars in the galactic plane. Credit: COBE/Goddard Space Flight Center/NASA.

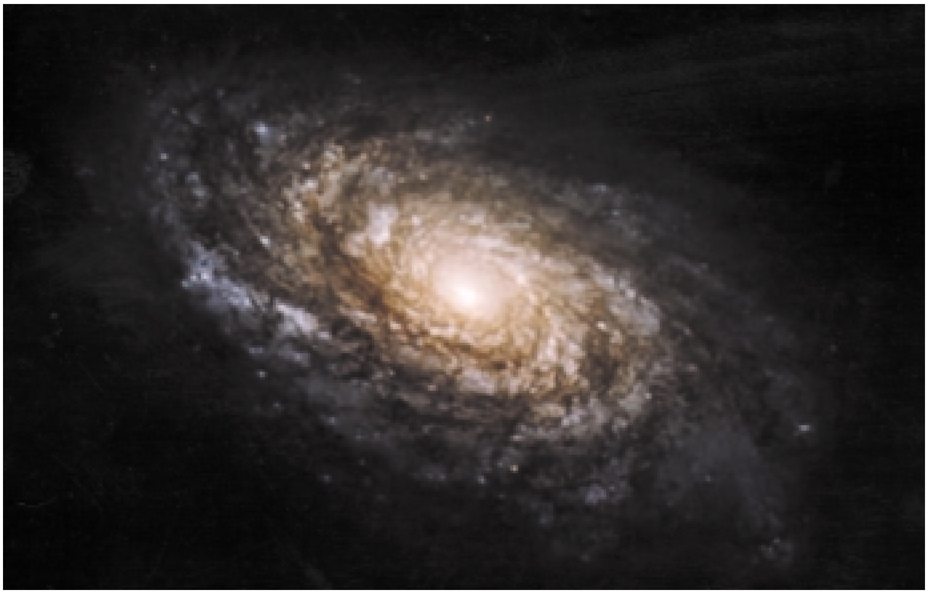


Figure 2. The spiral galaxy NGC 4414. We believe that our Galaxy, seen from outside, would resemble this spiral galaxy. Credit: Hubble Space Telescope Heritage Team (AURA/STScI/NASA).

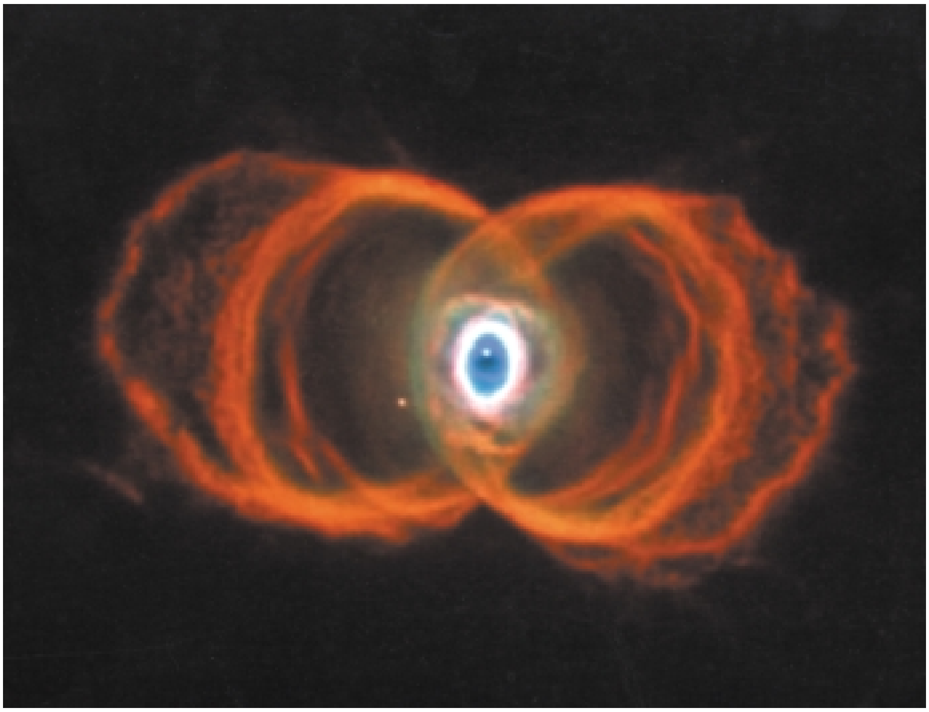


Figure 3. A Hubble Telescope image of the Hourglass Nebulae, a planetary nebula. The filaments are red because of the radiation from the hydrogen gas. Credit: R. Sahai and J. Trauger, the WFPC2 Science Team and NASA.