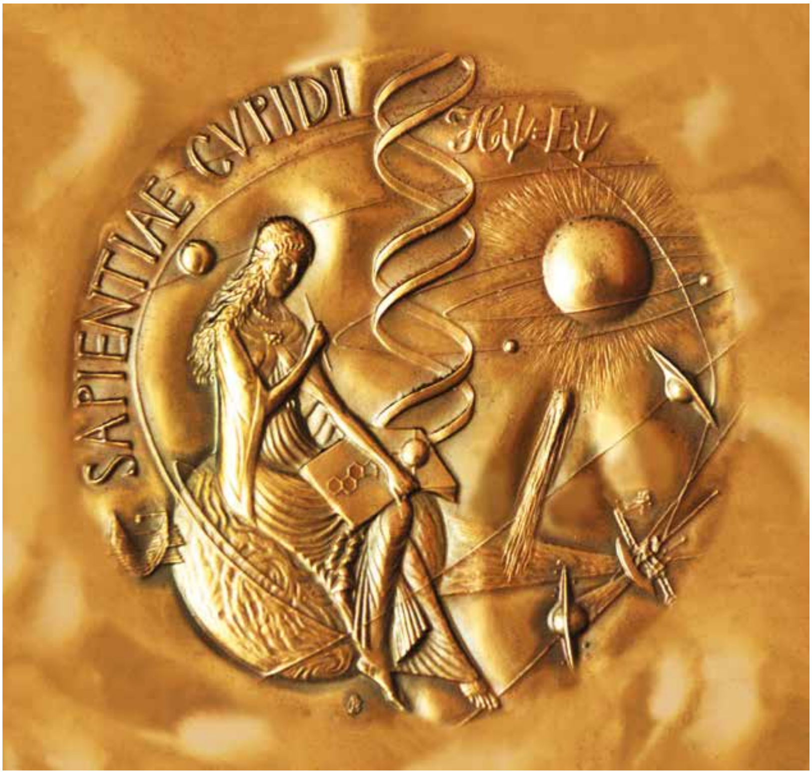
PONTIFICIA ACADEMIA SCIENTIARVM

PONTIFICIAE ACADEMIAE SCIENTIARVM ACTA 24

Edited by Werner Arber
Joachim von Braun
Marcelo Sánchez Sorondo

SCIENCE and SUSTAINABILITY

Impacts of Scientific Knowledge and Technology on Human Society and Its Environment



Plenary Session | 25-29 November 2016
Casina Pio IV | Vatican City

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Science and Sustainability. Impacts of Scientific Knowledge and Technology on Human Society and its Environment

Pontificiae Academiae Scientiarvm Acta 24

The Proceedings of the Plenary Session on

Science and Sustainability. Impacts of Scientific Knowledge and Technology on Human Society and its Environment

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Werner Arber
Joachim von Braun
Marcelo Sánchez Sorondo

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PONTIFICIA ACADEMIA SCIENTIARVM
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The climate is a common good, belonging to all and meant for all. At the global level, it is a complex system linked to many of the essential conditions for human life. A very solid scientific consensus indicates that we are presently witnessing a disturbing warming of the climatic system. In recent decades this warming has been accompanied by a constant rise in the sea level and, it would appear, by an increase of extreme weather events, even if a scientifically determinable cause cannot be assigned to each particular phenomenon. Humanity is called to recognize the need for changes of lifestyle, production and consumption, in order to combat this warming or at least the human causes which produce or aggravate it. It is true that there are other factors (such as volcanic activity, variations in the earth's orbit and axis, the solar cycle), yet a number of scientific studies indicate that most global warming in recent decades is due to the great concentration of greenhouse gases (carbon dioxide, methane, nitrogen oxides and others) released mainly as a result of human activity. As these gases build up in the atmosphere, they hamper the escape of heat produced by sunlight at the earth's surface. The problem is aggravated by a model of development based on the intensive use of fossil fuels, which is at the heart of the worldwide energy system. Another determining factor has been an increase in changed uses of the soil, principally deforestation for agricultural purposes.

Pope Francis, Encyclical *Laudato Si'*, §23.


A. ZICHICHI

Contents

Address of His Holiness Pope Francis to Participants in the Plenary Session of the Pontifical Academy of Sciences

Consistory Hall
Monday, 28 November 2016

Distinguished Ladies and Gentlemen,

I am pleased to welcome you on the occasion of your plenary session and I thank the President, Professor Werner Arber, for his kind words. I wish to thank you for the contribution you are making which, with the passing of time, increasingly reveals its usefulness for scientific progress, for the cause of cooperation between human persons and especially for the care of the planet on which God has allowed us to live.

Never before has there been such a clear need for science to be at the service of a new global ecological equilibrium. At the same time we are seeing a renewed partnership between the scientific and Christian communities, who are witnessing the convergence of their distinct approaches to reality in the shared goal of protecting our common home, threatened as it is by ecological collapse and consequent increase of poverty and social exclusion. I am pleased that you perceive so deeply the solidarity which joins you to the humanity of both today and tomorrow, in a sign of great care for mother earth. Your commitment is all the more admirable in its orientation towards the full promotion of integral human development, peace, justice, dignity and human freedom. Proof of this, in addition to the accomplishments of the past, is evident in the many topics you seek to examine in this plenary session; these range from great discoveries in cosmology, to sources of renewable energy, to food security, and even a passionate seminar on power and the limits of artificial intelligence.

In the Encyclical *Laudato Si'* I stated that "we are called to be instruments of God our Father, so that our planet might be what he desired when he created it and correspond with his plan for peace, beauty and fullness" (53). In our modern world, we have grown up thinking ourselves owners and masters of nature, authorized to plunder it without any consideration of its hidden potential and laws of development, as if subjecting inanimate matter to our whims, with the consequence of grave loss to biodiversity, among other ills. We are not custodians of a museum or of its major artefacts to be dusted each day, but rather co-operators in protecting and developing the life and biodiversity of the planet and of human life present there. An ecological conversion capable of supporting and promoting sustainable development includes, by its very nature, both the full assuming of our human responsibilities regarding creation and its resources, as well as the search for social justice and the overcoming of an immoral system that produces misery, inequality and exclusion.

Very briefly, I would say that it falls to scientists, who work free of political, economic or ideological interests, to develop a cultural model which can face the crisis of climatic change and its social consequences, so that the vast potential of productivity will not be reserved only for the few. Just as the scientific community, through interdisciplinary dialogue, has been able to research and demonstrate our planet's crisis, so too today that same community is called to offer a leadership that provides general and specific solutions for issues which your plenary meeting will confront: water, renewable forms of energy and food security. It has now become essential to create, with your cooperation, a normative system that includes inviolable limits and ensures the protection of ecosystems, before the new forms of power deriving from the techno-economic model causes irreversible harm not only to the environment, but also to our societies, to democracy, to justice and freedom.

Within this general picture, it is worth noting that international politics has reacted weakly – albeit with some praiseworthy exceptions – regarding the concrete will to seek the common good and universal goods, and the ease with which well-founded scientific opinion about the state of our planet is disregarded. The submission of politics to a technology and an economy which seek profit above all else, is shown by the "distraction" or delay in implementing global agreements on the environment, and the continued wars of domination camouflaged by righteous claims, that inflict ever greater harm on the environment and the moral and cultural richness of peoples.

Despite this, we do not lose hope and we endeavour to make use of the time the Lord grants us. There are also many encouraging signs of a humanity that wants to respond, to choose the common good, and regenerate itself with responsibility and solidarity. Combined with moral values, the plan for sustainable and integral development is well positioned to offer all scientists, in particular those who profess belief, a powerful impetus for research.

I extend my best wishes for your work and I invoke upon the activities of the Academy, upon each of you and your families, abundant divine blessings. I ask you please to not forget to pray for me. Thank you.

Introduction

We invite all members of the PAS to reflect on which already available or expected scientific advances may impact on the sustainable development of human societies and their environments. Please consider both positive and negative impacts. Some such impacts may become effective in the short term. But it is also important to keep in mind that sustainable development should hopefully contribute to life on Earth at the very long term, to maintain a relatively stable equilibrium of the human civilization in the steadily but slowly evolving world around us on our planet Earth.

At this Plenary Session we expect to receive specific inputs ideally from all scientific disciplines. We therefore invite all PAS Academicians to present their relevant contributions to the 2016 Plenary Session. Contributions can be either 20 or 10 minutes long, so that we will have sufficient time for discussions and for drawing conclusions.

Werner Arber

Word of Welcome

Good morning, I welcome all of you here. I'm pleased to see that quite a number of our Academicians took the time to come here to give their input and to help to find new ways for a topic which we formulated particularly wide, so that all scientific disciplines might, if they wanted, make some contributions for advancement in their disciplines and application of such advance of knowledge and implication of applications and knowledge after all on humanity.

We have of course, as you remember, the task to report to the Vatican for such advances and make propositions, recommendations how the Church could or might react. It's not our decision on how the Church has to react, that's the only thing which we can do, give good reasons and propositions so, in the course of the next few days, we hope to again formulate such recommendations and we expect that the Vatican will pay some attention to our work. We will be honoured by the Pope this year, on Monday, so we will have this occasion again for all of those who are here for this quite intensive meeting.

Since we decided that in the course of these four intensive days of discussion we wanted to spend particular attention on particular topics, we have organized three half-day meetings: one on cosmology, one on energy, and one on food. These are very important things, for if one speaks on sustainability – I did notice that the majority of us human beings think of the next one, two, at most three generations, but from my point of view if we are scientists, talking about sustainability in our developments we should think of much longer terms and I think we should pay attention to this discussion in the course of the next few days. That's not easy, we depend on models and expectations and, of course, often also on political decisions, but it's our opinion that if the Vatican can be properly informed on the advances and predictions on how these advances can progress and what are their applications, we can expect that, thanks to the worldwide network of the Catholic Church, the implications will have some effect on human civilization.

WERNER ARBER

Presentation of the Plenary Session

I am very interested in this meeting. As the President said, we have subjects that are really very important, like the question of the new forms of energy, the question of food security, the question of water, and we have been assured of the presence of the Pope. These are the most important questions today, also contained in the latest document of the Pope, the Encyclical *Laudato si'*, which asks for new forms of energy and also mentions the problem of food, and this subject is also in relation and in synergy with the new Sustainable Development Goals of the United Nations. All these things mean that our meeting has a special intensity also because we have, for the first time in a Plenary Session, invited specialists that do not belong to our Academy. I hope we can really arrive at an important contribution to the development of sciences for the sustainable development of the world.

Marcelo Sánchez Sorondo

Programme

Friday 25 November 2016

9:00 *Word of Welcome*
Werner Arber
Presentation of the Plenary Session
H.E. Msgr. Marcelo Sánchez Sorondo,
9:10 *Long Term Responsibility*
Jürgen Mittelstraß
9:30 *The Project for Mankind for a Sustainable Development of the World*
Antonino Zichichi
9:50 Discussion
10:10 Coffee break

NEUROSCIENCES AND SCIENTIFIC EDUCATION SESSION
Chair: Werner Arber
10:40 *Building a Bridge from Neuroscience to Education*
Stanislas Dehaene
11:00 Discussion
11:20 *Educating for Sustainable Development: A Crucial Role for Science Academies*
Pierre Léna
11:30 Discussion

SPECIAL SESSION
Cosmology on the Occasion of the 50th Anniversary
of Msgr. Georges Lemaître's Death (M.J. Rees)
Chair: Pierre Léna
11:50 *The Future of Space Exploration and Technology*
Martin J. Rees
12:00 Discussion
12:20 *Exploiting Solar System Resources: Opportunities and Issues*
Guy Consolmagno
12:30 Discussion
12:40 Lunch at the Casina Pio IV
14:50 *The Origin of the Universe*
Stephen W. Hawking

15:10 *The State of Understanding of the Nature and Evolution of the Observable Universe*
James P. Peebles
15:30 Discussion
15:45 *The Quantum Universe*
Robbert Dijkgraaf
16:05 Discussion
16:20 *What We Learn When We Learn that the Universe is Accelerating*
Saul Perlmutter
16:40 Discussion
16:55 Coffee break
17:25 *Thousands of New Worlds*
Lisa Kaltenegger
17:45 Discussion
18:00 *The Figure and Legacy of Msgr. Lemaître*
Thomas Hertog
18:20 Discussion
18:35 *Role of Space Technology for enabling inter-generational equity of natural capital and disaster resilience: Corollaries of Indian Space Program*
Krishnaswamy Kasturirangan
18:55 Discussion
19:10 *Scaling in Particle Physics and Cosmology*
Rudolf Muradyan
19:25 Discussion
19:35 Dinner at the Casina Pio IV

Saturday 26 November 2016

CHEMISTRY SESSION
Chair: Carlo Rubbia
9:00 *Atmospheric Chemistry and Sustainability*
Mario J. Molina
9:20 Discussion
9:40 *Novel Strategies for Energy Devices Based on Advanced Materials*
Chintamani N.R. Rao
10:00 Discussion
10:20 Coffee break

BIOLOGY SESSION

Chair: Carlo Rubbia

10:30 *Sustainable Cohabitation of Living Organisms*
Werner Arber

10:50 Discussion

11:10 *New Development in Genome Engineering: Scientific and Ethical Aspects*
Nicole Le Douarin

11:30 Discussion

11:40 *New Knowledge on the Causes of Human Congenital Malformations and its Impact on Society*
Edward M. De Robertis

12:00 Discussion

12:20 *The Challenges of Complexity in the Life Sciences and Society*
Wolf J. Singer

12:30 Discussion

12:50 Lunch at the Casina Pio IV

15:10 *My Sixty-Six Years of Medical Research*
Michael Sela

15:20 Discussion

15:40 *Impacts of Microbial Studies on Human Society and its Environment*
Takashi Gojobori

16:00 Discussion

16:20 *Plastics in the Ocean: A Current Perspective on Their Biodegradation*
Rafael Vicuña

16:30 Discussion

16:50 Coffee break

17:20 General discussion

HUMAN SCIENCES SESSION

Chair: Nicole Le Douarin

17:40 *Presentation on the Current Status of Organ Donation and Transplantation Around World – With the Dilemma of Organ Trafficking and Transplant Tourism*
Francis L. Delmonico

18:00 Discussion

18:20 *The Advancements in the Fight Against Cancer*
Salvador Moncada

18:40 Discussion

19:00 *The New Alliance Between Science, Policy and Religion in the Pursuit of Sustainability*
Veerabhadran Ramanathan
19:20 Discussion
19:40 Dinner at the Casina Pio IV

Sunday 27 November 2016

10:00 Council Meeting
13:00 Lunch at the Casina Pio IV
15:00 Closed Session
Past and Future PAS Activities
17:00 Coffee Break
17:30 Award Ceremony of the Pius XI Medal to Mariano Sigman
18:30 Holy Mass
19:30 Dinner at the Casina Pio IV

Monday 28 November 2016

SELF-PRESENTATIONS AND COMMEMORATIONS
Chair: Werner Arber
8:30 Self-Presentations
Francis L. Delmonico, Cédric Villani, Salvador E. Moncada, Hans Joachim Schellnhuber
9:10 Commemorations
Czesław Olech: Mathematics | Juan Maldacena
Walter Thirring: Physics | Carlo Rubbia
Alexander Rich: Biophysics | Werner Arber
Charles Townes: Physics | William Phillips
Georges M.M. Cottier: Philosophy | Jean-Michel Maldamé
Ahmed Zewail: Chemistry/Physics | Theodor W. Hänsch
Raymond Hide: Geophysics | Martin J. Rees
Mambillikalathil G.K. Menon: Physics | Chintamani N.R. Rao
10:00 Coffee break
10:45 Audience with Pope Francis, Hall of the Consistory, Apostolic Palace
11:45 Presentation of the Proceedings of the International Colloquium of April 2013 entitled "Sur le chemin de l'Humanité. Via humanitatis. Les grandes étapes de l'évolution morphologique et culturelle de l'Homme. Émergence de l'être humain", co-edited by the Pontifical

Academy of Sciences and by CNRS Editions. Interventions by the President Werner Arber and Professor Henry de Lumley

13:00 Lunch at the Casina Pio IV

SPECIAL SESSION

Energy (T.W. Hänsch)

Chair: Theodor Hänsch

14:30 *Introduction*
Theodor Hänsch

14:45 *Energy in Perspective*
Stephen Chu

15:15 Discussion

15:30 Coffee break

15:45 *The Future of Energy*
Carlo Rubbia

16:05 Discussion

16:20 *Solar Cells and Solar Energy*
Klaus von Klitzing

16:30 Discussion

16:40 *What to Expect from Nuclear Fusion Energy*
Sibylle Günter

17:00 Discussion

17:15 *New Prospects for Electrical Batteries*
Yi Cui

17:35 Discussion

17:50 *Sustainable Thorium Energy for the World*
Jean-Pierre Charles Revol

18:10 Discussion

18:25 *Efficient Use of Electrical Power in the Context of Sustainability*
William Phillips

18:35 Discussion

18:45 General Discussion

19:40 Dinner at the Casina Pio IV

Tuesday 29 November 2016

PHYSICS SESSION
Chair: William Phillips

09:00 *New Photonic Ways to Control Local Infections in Young Kids – Avoiding the Antibiotic Catastrophe*
Vanderlei S. Bagnato
09:10 Discussion
09:30 *Down the Carbon Staircase!*
Hans Joachim Schellnhuber
09:50 Discussion
10:10 Coffee Break

SPECIAL SESSION
Food & Nutrition – The Role of Biotechnology in Agriculture
(Joachim von Braun and Ingo Potrykus)
Chair: William Phillips

10:40 *Welcome and Introduction*
Ingo Potrykus
11:10 *The Need for Sustained Improvements*
Joachim von Braun
11:25 Discussion
11:35 *Increasing Crop Yield Potential: A Role for Genetic Modification?*
Peter Beyer
11:50 Discussion
12:00 Lunch at the Casina Pio IV
13:30 *Reducing Mineral and Vitamin Deficiencies Through Biofortification: Progress Under HarvestPlus*
Howarth Bouis
13:45 Discussion
13:55 *Effects on Biodiversity*
Peter Raven
14:10 Discussion
14:20 *Sustained Soil Management – "No Till" – Agriculture*
Mariano M. Bosch
14:35 Discussion
14:45 *Socio-Economic Impacts Pro Poor*
Matin Qaim
15:00 Discussion

15:10 *The Role of the Public Sector – "New Technologies"*
Marc van Montagu

15:25 Discussion

15:35 *The Role of Plant Biotechnology in Human Health. Public Sector Constraints: The Golden Rice Experience*
Adrian Dubock

15:50 Discussion

16:00 Coffee Break

16:30 *The Devastating Effect of Regulation and the Nobel Laureate Campaign in favor of GMOs*
Richard J. Roberts

16:45 Discussion

16:55 *Summary*
Joachim von Braun

CLOSING SESSION

17:40 General Discussion and Final Statement

19:40 Dinner at the Casina Pio IV

List of Participants

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Buenos Aires (Argentina)

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(USA)

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The Pius XI Medal Award

MARIANO SIGMAN

Brief account of scientific activity

Mariano Sigman was born in Argentina and grew up in Barcelona, Spain. He obtained a master's degree in physics at the University of Buenos Aires and a PhD in neuroscience in New York. He moved to Paris to investigate decision making, cognitive architecture and consciousness. In 2006 he founded the Integrative Neuroscience Laboratory, at the University of Buenos Aires, an interdisciplinary group integrated by physicists, psychologists, biologists, engineers, educational scientists, linguists, mathematicians, artists and computer scientists.

His lab has developed an empirical and theoretical approach to decision making, with special focus on understanding the construction of confidence and subjective beliefs. Many aspects of his investigation rely on data mining and computational tools on massive corpus of human behavior. Recently, he has progressively shifted his research to understand how current knowledge of the brain and the mind may serve to improve educational practice. Many of the projects conducted are developed at schools throughout the country and he is extending these investigations on cognitive development to hundreds of thousands of children through the One Laptop Per Child (OLPC) framework.

Throughout his career he has developed numerous research interactions with representatives of different domains of human culture including, musicians, professional chess players, mathematicians, magicians, visual artists and chefs. He has also pursued an arts career with exhibits presented in museums and galleries in Argentina, Mexico, Brazil, US, Japan, New York, Austria...

Selected publications

Di Tella, R., Perez-Truglia, R., Babino, A. & Sigman, M. Conveniently Upset: Avoiding Altruism by Distorting Beliefs about Others' Altruism. *The American Economic Review* 105, 3416-3442 (2015).

Meyniel, F., Sigman, M. & Mainen, Z.F. Confidence as Bayesian Probability: From Neural Origins to Behavior. *Neuron* 88, 78-92 (2015).

Reis, S.D.S. et al. Avoiding catastrophic failure in correlated networks of networks. *Nature Physics* 10, 762-767, doi:10.1038/nphys3081 (2014).

Goldin, A.P. et al. Far transfer to language and math of a short software-based gaming intervention. *Proceedings of the Na-*

tional Academy of Sciences 111, 6443-6448, doi:10.1073/pnas.1320217111 (2014).

Sigman, M., Peña, M., Goldin, A.P. & Ribeiro, S. Neuroscience and education: prime time to build the bridge. *Nature Neuroscience* 17, 497-502, doi:10.1038/nn.3672 (2014).

Gallos, L.K., Makse, H.A. & Sigman, M.A small world of weak ties provides optimal global integration of self-similar modules in functional brain networks. *Proceedings of the National Academy of Sciences* 109, 2825-2830 (2012).

Zylberberg, A., Dehaene, S., Roelfsema, P.R. & Sigman, M. The human Turing machine: a neural framework for mental programs. *Trends in Cognitive Sciences* 15, 293-300 (2011).

Bekinschtein, T.A. et al. Classical conditioning in the vegetative and minimally conscious state. *Nature Neuroscience* 12, 1343-1349, doi:10.1038/nn.2391 (2009).

Corallo, G., Sackur, J., Dehaene, S. & Sigman, M. Limits on Introspection Distorted Subjective Time During the Dual-Task Bottleneck. *Psychological Science* 19, 1110-1117 (2008).

Gilbert, C.D. & Sigman, M. Brain States: Top-Down Influences in Sensory Processing. *Neuron* 54, 677-696, doi:10.1016/j.neuron.2007.05.019 (2007).

Sigman, M. et al. Top-Down Reorganization of Activity in the Visual Pathway after Learning a Shape Identification Task. *Neuron* 46, 823-835, doi:10.1016/j.neuron.2005.05.014 (2005).

Sigman, M. & Cecchi, G.A. Global organization of the Wordnet lexicon. *Proceedings of the National Academy of Sciences* 99, 1742-1747 (2002).

Memory Introspection

Mariano Sigman

Science is about making visible the invisible. The discovery of telescopes allowed scientists in the Renaissance to observe for the first time the most remote and distant corners of the solar system. And with this, solve fundamental questions which for centuries had only been a matter of speculation. In recent years, the instruments and vessels of science have also transformed our capacity to observe human brain activity. This, in turn, has solved controversies about the human mind, which had so far been exclusively a matter of philosophical conversation. For example, we can delve into the dreamer brain, decoding the content of dreams in real time, establishing concisely that dreams occur in real time and are not "just" figments of memory of the awakened mind. Or, from a more medical perspective, to decipher the thoughts of vegetative patients asking if they may have residues or preserved forms of consciousness which might not be expressed overtly. Human thought has never been so transparent.

But all this technology is, of course, useless for investigating one of the most mysterious aspects of human thought. How it came to be what it is. How were the thoughts of our ancestors? We know that their brains were almost identical to ours. But were they conscious in the same way we are today?

There are different intuitions about this longstanding philosophical debate. On one hand, it is natural to think that the deepest aspects of human thought – our ability to be conscious, to form memories, to imagine or to dream – have always been the same. Another possibility is that the social transformations that have so radically shaped our culture may even have forged these structural columns of our thoughts. Without the capacity to use all our technological paraphernalia to investigate brain function, is this question even amenable to science?

The solution to this conundrum is in the traces that our ancestors have left, not only of what they did, of how they lived or fought, but also of how they thought. In the same way that we can reconstruct how the ancient Greek cities looked like, just based on a few bricks, the writings of a culture are the archeological records, the fossils of human thought.

And in fact, doing some form of psychological analysis on some of the most ancient books of human culture, in the seventies Julian Jaynes came with a wild and radical hypothesis: that in about 3000 BC the world was a "garden of schizophrenics".

Jaynes read exhaustively the human writings in the axial-age – a period approximately between 800 and 200 BC, which marked a radical transformation in Chinese, Indian and Western civilizations. It was during this period that the religions and philosophies that form many of the pillars of modern culture were produced. Studying these foundational texts, Julian Jaynes argued that during this period, human consciousness also went through a radical transformation.

He argued that the first humans described in these books behaved – in different traditions, in different places of the world – as if they were hearing and obeying voices that they perceived as coming from gods or muses, which today we would call hallucinations. And then, only as time went on, they progressively began to understand that they were the creators and owners of these inner voices. And with this, they acquired introspection: the ability to think about their own thoughts.

This may seem quite strange and paradoxical at first, but as with most human abilities that we take for granted, upon reflection it becomes clear that they ought to be forged in a learning process, either through the span of life, culture, or evolution. We all produce inner voices, inner thoughts. Most of us understand that we are the authors of these inner voices. But what if, as often happens during dreams, we do not? Chris Frith, a brilliant cognitive neuroscientist, has argued that this inability may be at the heart of schizophrenia. In this view, hallucinations do not result so much from a vast excess in fueling mental creations, but more in the incapacity to recognize the authorship of such creations.

According to Jaynes, consciousness, prior to Homer, lived in the present and lacked introspection, what now we call primary consciousness and is characteristic of schizophrenia or dreams (except for lucid ones). With the proliferation of texts, consciousness transformed into what we now recognize, a form of consciousness in which we perceive we are the authors, protagonists and people responsible of our inner thoughts and actions, a consciousness which, in turn, has the richness to interweave with what we know of the past and what we predict or hope for the future.

Jaynes and others have argued that the appearance of written texts was at the heart of this psychological revolution, because it allowed thought to be consolidated on paper instead of being entrusted to the more volatile memory. We should remind those who now reflect so much on how the Internet, tablets, cell phones and the unceasing flow of information can change the way we think and feel, that the information age is not the first material revolution to radically change the way we express ourselves, communicate and, almost certainly, think.

In summary, Jaynes' theory is that consciousness, at least in the way we perceive it today, when we feel we are the pilots of our own existence, is a quite recent cultural development. This conjecture remains as one of the most polemical, controversial and speculative in cognitive neuroscience*, among other things* because it relies on very specific examples and subjective interpretations. It was in fact difficult, if not impossible, for Jaynes (and others, at that time) to establish these claims in a quantitative and objective manner. The reason is quite simple: the word introspection (or self-consciousness) that Jaynes argued appeared throughout the axial-age, is not mentioned a single time in the books he studied.

Things would have been much easier for Jaynes' theory if Plato woke up one day writing: "Hello, I'm Plato, as of today I have a fully introspective consciousness". But this, of course, did not happen.

The development of introspection must be read in between the lines. And here is where psychology meets philology, computer science and linguistics. Doing so requires a more sophisticated mathematical entity than simply counting words: the construction of a "space of words". This is a huge, complex and high dimensional space that contains all words in such a way that the distance between any two of them is indicative of how closely related we feel they are. So one would want in this space the words 'dog' and 'cat' to be close together, but the words grapefruit and logarithm to be very far apart. *And this has to be true for any two words in this space.*

Computational linguistics has shown us that this space can be built quite easily using a simple but effective premise: when two words are related, they tend to appear in the same sentences, paragraph or page, when aggregated over a very large corpus of text. One can then formally define the proximity of any two given words as their likelihood of appearing together in a vast summary of all human linguistic expressions, compared to how often they would appear together simply by pure chance.

Once this space has been constructed, establishing which of two texts is closer to a given concept, is not just a qualitative argumentation but instead a concrete, objective and quantifiable argument. And with this one can inquire about the history of any concept, including introspection, asking how it grows, fades up or down, vanishes and changes in time. A text becomes a stream of words, a stream of words becomes a trajectory in the space of meanings. And then using simple geometry one can ask whether this trajectory approaches any given concept.

And when this is done after digitalizing the books of the Ancient Greek Tradition, ordering them by time, measuring the proximity of each word of this stack of books to introspection, one finds that, as Jaynes had conjectured, these texts become closer with the passage of time to the concept of introspection. There is a slow progression for the older Homeric texts: the Iliad and the Odyssey. And then, about 600 years before Christ, throughout the development of the ancient Greek culture, it begins to ramp up very rapidly to an almost five-fold increase with writings becoming closer and closer to introspection.

A fundamental virtue of an objective and quantitative analysis is that one can replicate the exact same results in a different case, asking whether these results are also true in a different and independent tradition. And, indeed, when this analysis is repeated for the Judeo-Christian books, or for a whole set of traditions throughout the axial-age, one obtains essentially the same pattern.

With this exercise in quantitative philology, using computational tools in humanity's historic archives, Carlos Diuk, Guillermo Cecchi, Diego Slezak and I were able to test Jaynes' "soft" hypothesis that there is a change in the narration of Homeric and Biblical texts that reflects an introspective discourse. In our view, however, it is not possible to examine the "hard hypothesis", settling whether this change reflects the filter of written language, censorship, narrative trends and styles, or whether, as Jaynes conjectures, it expresses the way our ancestors thought. Resolving this dilemma requires ideas and tools that we have yet to even imagine.

Self-Presentation of the New Academicians

Francis L. Delmonico

Thank you, Mr. President. Good morning, everyone. I'm an organ transplant surgeon, a physician and surgeon for 45 years. I'm of the second generation of transplant physicians and surgeons, following in the footsteps of Joseph Murray, who was the recipient of the Nobel Prize for kidney transplantation, a mentor to me, a member of this Academy.

My home hospital is the Massachusetts General Hospital in Boston. As an academic, I'm a Professor of Surgery at the Harvard Medical School. As a scientist, my interest is to expand the opportunity of transplantation for patients with organ failure around the world, and do so by a reproducibility, a consistency of assessing the organ in advance before transplantation. I've had the honour to be the President of the organ donation agency that oversees transplantation in the United States. I've had the honor to be the President of The Transplantation Society, that has representatives in more than 100 countries that have transplant services around the world, and I've traveled to 75 countries to participate and develop organ donation and transplantation in those countries.

My work with the Academy and, by the way, as an identity of the Chief Medical Officer of the New England Organ Bank, which I've been associated with for 25 years, is to achieve an ethically proper and scientifically achievable expansion of deceased organ donation in all countries that have these services and to bring an ethically proper living organ donor transplantation that safeguards and protects the well-being of the living donor.

So that is my work and effort, and again I thank you for the opportunity of making this presentation. Thank you, President Arber. It's a special honor for me to receive this from the Chancellor, for whom I have great regard.

Cédric Villani

I am a mathematician and I am a specialist of analysis, mathematical physics, probability and geometry combined with analysis being my main entry point. For a long time I used to say that the most important common point between my works was the notion of mathematical entropy. Let me recall that this notion was introduced by the Austrian physicist Ludwig Boltzmann in mathematical terms around the end of the 19th century as part of the scientific ping-pong game that he was playing with James Clerk Maxwell in order to develop atomistic theory.

It was in those days an enormous stretch of thought to think that when you are in a quiet room like the one we are in today, with the zero wind that we can feel, actually this vision of something very quiet has to be replaced by the very chaotic vision of billions of billions of particles bumping on each other constantly, and that vision was rejected by many prominent scientists at the time. It was even more a stretch of thought, and I think that Bushman was the only one to believe that, at some point, some of the most fundamental laws of physics that we see always applied would actually rest on probabilistic and statistic formalism, because we have this idea that probability is the realm of what is uncertain and unpredictable. But eventually the ideas of Boltzmann triumphed and were influential in a number of fields which led to the experimental discovery of atoms at the beginning of the 20th century and many other adventures, since entropy is now recognized as one of the fundamental driving forces of physics. But entropy also made a major role in communication theory, since it turned out to be at the center of the theory of communication developed by Shannon in the Bell Labs, and spreading around the science thereafter, and entropy also turned out to be an extraordinarily important concept for mathematics in itself.

So in this field and in this concept I was lucky enough to bump into several contributions and with several pieces of great luck. One of these lucky developments in my career was for my first professional visit to Italy, when I visited Professor Giuseppe Toscani in Pavia and he had an idea to prove a certain conjecture about the instantaneous increase of entropy in spatially homogeneous gases, the so-called Cercignani conjecture, after the late Carlo Cercignani. I was a young PhD student in those days with a lot of time, and he was director of a laboratory, so he had no time at all, so he gave me the idea and I set up to work it out. I found quickly that it was a very naive and rather stupid idea, but in the process of checking it and making the computation I bumped into a beautiful formula which I thought was too beautiful to be useless. It turned out that this formula was the start of the solution of the problem and the start of many works on this subject with Toscani and with other people, like Laurent Desvillettes. The general goal was to understand from a mathematical point of view quantitatively how entropy increases in a gas. One of the main difficulties for this was to understand and capture the tension that there is in the gas between the phenomenon of information transfer through collisions of particles and fluid mechanics. Now in physics, mathematical physics, many of the important and fascinating equations are related to the tension of two phenomena. Now, as we know in biology, it's such a complicated situation because you have all the time dozens of phenomena going together at the same time, but in physics very often we can isolate just the contradiction between two, and part of my work was made in that.

Another piece of luck in my career was when I happened to be reading a course on probability by Michel Ledoux, just a few weeks after hearing the talk of a young German mathematician, Felix Otto, using the notion of entropy to define the heat equation in a novel way. I recognized that there was a relation between these two things and this was the start of another piece of mathematics in which entropy played a fundamental role, this time applied to non-Euclidean geometry, and we were the first of a group of people who understood that you can read the so-called Ricci curvature bounds through the evolution of entropy in a gas which is constrained by laws of minimal motion. This implied developments of an unexpected type in geometry and turned out to my spending a couple of years of my life writing a big reference book on the subject. The reference book was about a thousand pages long. If I wanted to write it again seven years later it would have to be 2,000 pages, since the subject has grown so far, so fast from that time and completely overcame my modest achievements, in a way.

However, the most visible part of my work came from understanding relaxation in another field, another mathematical physics field, which is the theory of plasmas and the so-called Landau Damping effect, which was suggested by Laughlin in the 1940s, according to which, in the plasma, there are relaxation phenomena which do not involve the increase of entropy and which are rather related to mixing, parallel to what astrophysicists call 'violent relaxation' in galaxies, and it was part of a new conceptual revolution, 70 years after Boltzmann, according to which entropy increase and irreversibility was not the only source of stability. I spent two years together with my former student Clement Mouhot tracking this Landau Damping effect in the mathematical world, in the nonlinear world, and this resulted in a 150-page long proof of that Landau Damping, which was also the start of a new field of research related to relaxation with non-entropic effects. This eventually led me to be lucky enough to receive the Fields Medal in 2010 for this set of works on stability. It was the start of another part of my career with a lot of public outreach, administration, public lectures going in the media and trying to improve the perception of science by society, working also for being involved in the development of science in Africa, among other things.

In this Academy I hope to be able to participate constructively in the debates at a time in which mathematics has taken more importance than ever, not only in science but also in society at large, seen through the rise of algorithms, which now play a major role in the public debate in society. This is my first time here as a member and it is a great honor for me.

Salvador Moncada

I was born on 3 December 1944 in Tegucigalpa, Honduras, from a Honduran father of Spanish descent and a Jewish mother born in Romania in Chernowitz, now known as Chernivsty and located in Ukraine. Her family escaped Europe in 1938-39 and, following a series of unexpected events, settled in Honduras. Hers was a German speaking family which continued to speak mainly German for the rest of their lives. A number of her relatives were persecuted and disappeared during the war. My mother was a housewife and my father, although trained as a medical doctor, never practiced medicine and became a businessman. My family moved from Honduras to El Salvador in 1948 where I lived for the next twenty-two years.

I grew up in a happy household. My father was Latin American from a Catholic family and my mother an Eastern European Jew. Neither of them was religious but they possessed defined cultural stereotypes. This created a rich environment, often contradictory, but always respectful and provided me with a wide perspective on things. I developed an early interest in biology and medicine and remember collecting insects and devising ways of keeping them in captivity to observe them. I would also, when they died, dissect them to see their internal organs. This was at about the age of eight or nine. By the time I was eleven I was determined to study medicine and to do research as the only career option in my life. I also developed, from very early on, an awareness of injustice, which I could see all around me. This led to early political activism and denunciation of the ills of the society I belonged to.

I have been married twice, in 1966, in El Salvador, to Dorys Lemus Valiente, a biochemist. We had two children: Claudia Regina born in1966, now a medical doctor in general practice, mother of two and living in London, and Salvador Ernesto, born 1972 and deceased in 1982.

In 1998 I married Princess Esmeralda de Belgique. We have two children, Alexandra Leopoldine born 1998 and Leopoldo Daniel born in 2001.

From 1951-56 I attended the Colegio Bautista in San Salvador. It was a high quality primary school in our neighbourhood and the Director at the time was Evalena McCutcheon, a North American who had lived in El Salvador for many years. She was an excellent teacher and a significant influence on our lives.

From 1957-61 I attended the Instituto Nacional "General Francisco Menéndez", which had previously been a military academy and provided a high standard of education as well as strict discipline. I was sent to this school, attended by children from working class and poor families, because my father thought it important for me to understand the living conditions of people in the country.

From 1962-70 I studied medicine at the Facultad de Medicina, Universidad de El Salvador. At that time it was one of the best medical schools in Central and South America, since it had recently been updated and restructured along the lines of modern medical schools in the USA. This was carried out by a group of distinguished Salvadoran doctors who had previously trained in the US and other places. Chief among them was María Isabel Rodríguez, a Salvadoran cardiologist of high scientific and clinical repute, who became my mentor. The medical school had a programme of visiting scientists, through which I met Augusto Campos, a Peruvian pharmacologist who had trained in the US working on the pharmacology of the sympathetic system. He provided my introduction into pharmacology and to medical research.

When I started medical school, my particular interest was in science and I intended to combine research with medical practice. During my clinical years, however, working in the various hospitals I was deeply disturbed by the poverty of the majority of the population of El Salvador and realised that their medical needs could only be addressed by structural changes in society leading to improvements in public health. As a result of this I became politicised and interested in training in Epidemiology and Public Health. Politics in El Salvador at that time was of a militant nature and by June 1970, immediately after I graduated, I was captured by the secret police, beaten up and expelled from El Salvador into Honduras. All this happened shortly after the border war between EI Salvador and Honduras, which created animosity between the people of the two countries. In Honduras, I started to work in the Department of Physiology in the University of Honduras, accepting the only job available in the Faculty of Medicine. This marked my return to basic medical sciences, my original interest.

My wife and child were not allowed to join me there as they were Salvadoran so we were obliged to meet when we could in Guatemala, the country in between. In order to keep my family together I realised that I had to go abroad. A Guatemalan doctor – Fernando Molina – had spent some time in the UK at the Royal College of Surgeons where he had met John Vane. Molina suggested that we write to John to see if he could give us some advice about post-graduate education in the UK. John replied, inviting me to come to work in his laboratory based on the recommendation of Molina.

I arrived in London on 19 February 1971. John Vane was a Professor in the Department of Pharmacology in the Institute of Basic Medical Sciences at the Royal college of Surgeons. The environment in the department was highly interactive and intellectually stimulating with many distinguished British and foreign scientists working there. I was lucky because at the time of my arrival the hypothesis about the potential mechanism of action of aspirin and other non-steroidal anti-inflammatory drugs was being discussed. I was invited to join the project and set to work on a series of successful experiments that a few months later formed part of a landmark trio of publications in the journal *Nature*. Those papers explained the mechanism of action of these drugs and also their main side effect of gastric damage. The result was that I found the work in the laboratory so exciting and consuming that I never thought to go back to the practice of clinical medicine. This is something that I do not regret, although I have always felt that my research has been guided by my medical knowledge that gives me an integrated vision of physiology and pathophysiology.

Between July 1974 and July 1975 I went back to Honduras, where I set up a laboratory at the Medical School. However, the conditions in the country were not conducive to research and therefore the following year I returned to the UK at the invitation of John Vane to lead a research group at the Wellcome Research Laboratories in Beckenham, Kent. John had become overall R&D Director of the Wellcome Foundation.

By then I had become interested in platelets and their role in vascular disease. This was a significant and very productive change of direction since, within a year, we had discovered an enzyme in platelets that generated thromboxane A2, a powerful vasoconstrictor and platelet-aggregating substance and shortly afterwards, in the vascular wall, we discovered prostacyclin, a vasodilator with potent anti-platelet aggregating properties. Since the platelets and the vessel wall generate substances with opposing biological properties I thought that this was a balancing system in the vasculature of pro- and anti-thrombotic tendencies. This hypothesis is now widely confirmed. The fact that the generation of thromboxane A2 is inhibited by very small concentrations of aspirin, without affecting the generation of prostacyclin in the vessels, has led to the widespread use of small doses of aspirin for the prevention and treatment of cardiovascular disease and as a result, millions of people currently benefit from those discoveries. Furthermore, the "balance hypothesis" has explained, more recently, the cardiovascular side effects of the anti-inflammatory agents called COX2 inhibitors, which preferentially inhibit the generation of prostacyclin in the vasculature.

I remained at Wellcome for the next twenty years, occupying different positions, first as leader of the Prostaglandin Research Group, then head of the Department of Prostaglandin Research until 1985, when I became Director of Therapeutic Research and finally, in 1987, Director of Research (UK).

In 1984 I became interested in endothelium-derived relaxing factor (EDRF) discovered by Furchgott a few years earlier and began a project which led us to its identification as nitric oxide (NO). We also elucidated the pathway to its biosynthesis from the amino acid L-arginine and revealed many of the biological actions. Our findings led me to propose that the "L-arginine: NO pathway" is a widespread transduction mechanism for regulating cell function and communication. This turned out to be the case following the finding of nitric oxide in the peripheral and central nervous system as well as in other systems including the immunological system. The implications of the discovery of this novel mediator continue to be explored, but it is clear that it has represented a significant advance in our biological knowledge and that it is providing clues for the prevention and treatment of disease.

I worked at the Wellcome Research Laboratories until 1995. In my tenure as Research Director I directed and oversaw the discovery and development of a number of useful medicines including lamotrigine (anti-epileptic), zomig (anti-migraine), atovaquone (anti-malarial) and the initiation of the project that led to the anti cancer compound, lapatinib.

The market pressures on the drug industry were being increasingly felt at Wellcome, which not only was owned by the Wellcome Trust, the only shareholder, but was a highly academic institution successfully combining discovery research with research for drug discovery. It was evident that the pharmaceutical industry was becoming much more marketing- and development-orientated than research-based. Following the buying of

Wellcome by the pharmaceutical company Glaxo, I moved to University College London in January 1996 to establish and direct the Wolfson Institute for Biomedical Research (WIBR), originally known as the Cruciform Project. My main aim was to set up a centre of excellence in biomedical research that would be an interface between fundamental research and its application – a translational research centre. This approach led to the setting up of a number of spinout companies, including Ark Therapeutics, Arrow Therapeutics, CereXus, Inpharmatica, ProAxon, Canbex Therapeutics and Domainex. My work during the WIBR years was dedicated to exploring new areas, including that of mitochondrial biology and, later, the metabolic basis for cell proliferation.

In 2013 I moved to the University of Manchester where I was Director of the Institute of Cancer Sciences from February 2014 to 2016 and then of the Cancer Domain from 2016. In those capacities I rapidly became aware that prevention and early detection of cancer is the only way to manage this disease. The drug treatment of an increasing number of people with increasingly expensive treatments and follow-up procedures is not viable and is illogical. I have promoted this view extensively.

Besides experimental science, I have long been interested in higher education and in society issues relating to the plight of the less developed countries. I have, as a result, worked as a consultant for the World Health Organisation for Latin America. I am committed to finding ways to aid the scientific and technical development of the third world. I was a founder member of Honduras Global – a network of successful Hondurans living abroad and interested in helping the country – and am still actively working with this organisation. I have had particular interest in the study of political philosophy and am a keen student of the British philosophers, including Hobbes, Locke and Hume.

I am specially honoured to be here today to join the Pontifical Academy, so full of talent, where I hope to contribute to achieve a better world for all mankind.

Hans Joachim Schellnhuber

Good morning everybody. My name is Hans Joachim Schellnhuber. I'm very honored to be here this morning, as a member of the Academy, and to have the opportunity to provide a brief short presentation. My professional life revolves around three notions actually: physics, complexity and climate. In my early stage of career I worked in condensed matter physics, so I had the privilege to work with Gregory Wannier and Walter Kohn, who passed away last year, and I had a chance to solve a fundamental physics problem in my PhD on crystal electrons in magnetic fields.

When I moved to California to join the then emergent field of what was called at the time 'chaos science' – now it has a much more respectable name, it's called Complex Nonlinear Dynamics – but there was this popular notion at the time that the flap of the wing of a butterfly could create a storm: it's also the other way around, by the way, a storm can create the flap of the wing of a butterfly, we never know. So, since in my PhD I was also involved in work on number theory, it turned out that so-called irrational magnetic fields play a big role and that was the first fractal in solid state physics, so I walked into that field and had the privilege to work in Santa Barbara with a number of eminent people.

I went back to Germany, and I tried to apply this nonlinear dynamics to environmental systems among all of us because, you know, the forming of clouds, for example, is a highly nonlinear complex process, and when my personal flap of a butterfly's wing happened, because something highly nonlinear happened in Germany in 1989, the Berlin Wall came down (you know, nobody had really predicted that and we Germans thought the wall will be around for another hundred years or so, but it came down), which means that a number of new institutions were set up in the eastern part of Germany, in particular on this famous campus on Telegraph Hill in Potsdam, where Albert Einstein worked and Karl Schwarzschild actually solved Einstein's field equations for the first time and Albert Michelson did the first version of his famous experiment.

So, I was asked to found the Potsdam Institute on Climate Impact Research and I've worked in that field ever since, but I tried to in particular connect it to the nonlinear dynamics. Climate science and complexity science in my view really belong together, and now the Potsdam Institute has about 400 members working on all dimensions of climate change and my field is still nonlinearities in the climate system and I'm going to present that also tomorrow, when I have a chance to give a lecture on that, because, you know, we still are not sure whether the human interference with the climate system has already instigated something like a runaway greenhouse effect, we simply do not know yet and it's one of the most exciting, but I guess also most relevant issues for humankind. And you know, the Symposium is about science and sustainability, so I'll address this question tomorrow.

Let me conclude by saying that in the course of these years I have also given advice to policymakers and society at large about the threat of climate change and environmental degradation, so maybe just two things in this context: I had the big honor to make a contribution to the presentation of the Encyclical *Laudato Si'* last June, here in the Vatican, at the Pontifical Academy under the leadership of Marcelo Sánchez Sorondo, and V. Ramanathan here made a very important contribution, sort of corroborating the science behind it; and I have been advising the German Chancellor, Angela Merkel, for more than 20 years in a personal capacity. In 1994 I recall when I first proposed to her that we should have something like a 2 degrees target for global warming and, you know, last year in Paris this became international law, so you can see, sometimes even a humble physicist can make a little contribution. Thank you very much.

Commemorations of Deceased Academicians

Walter Thirring († 18.VIII.2014)

Walter Thirring left us on 19 August 2014 in his 87th year. He was an Austrian physicist after whom the Thirring model in Quantum Field Theory was named.

Walter Thirring was born in Vienna, where he earned his Doctor of Physics degree in 1949 at the age of 22. In 1959, at the remarkable age of 32, he became Professor of Theoretical Physics at the University of Vienna.

Thirring participated in challenging and profound life experiences, growing up under Nazi occupation, serving in the war, striving to establish scientific excellence and reaching out across the Iron Curtain.

Thirring is one of the last physicists who worked on the greatest discoveries and with the greatest scientists of the 20th century. He recollected his encounters with old masters like Einstein, Schrödinger, Heisenberg, Pauli and others.

Starting from his degree in 1949 Walter Thirring extensively travelled abroad. He worked for one year with Erwin Schrödinger in Dublin, with Werner Heisenberg in Göttingen and Wolfgang Pauli in Zürich. In 1953, when he was 25, he went to Princeton and met Albert Einstein, 48 years his senior. During the two long encounters, they discussed politics, freedom and, of course, physics. A healthy mutual skepticism developed between the two men over new ideas about Gravitation and about the influence of Quantum Mechanics.

Thirring held various positions at other leading institutes and universities such as the Swiss Federal Institute of Technology (ETH Zürich), the Institute for Advanced Study in Princeton, and the Massachusetts Institute of Technology.

He then returned to Vienna, teaching as Professor at the University of Vienna until 1968, when he took the position of Head of the Theoretical Physics group at CERN which he held up to 1971.

I personally met Walter when he arrived at CERN in 1968. Our friendship continued since then in very different locations and most importantly during my visits to Austria where meeting him amongst my many friends was for me a recurrent event.

Besides pioneering work in quantum field theory, Walter Thirring devoted his scientific life to mathematical physics. He is the author of many scientific papers, of one of the first textbooks on quantum electrodynamics as well as of a four-volume course in mathematical physics, which he published during a 10-year-long period from 1888 to 1998.

In his writings he presented the challenges faced when the shift away from atomistic theory and Newtonian physics towards field theory and quantum mechanics took place. Every step is presented in clear, understandable language that reflected Thirring's extensive experience in training the next generations.

In 2007 Walter Thirring authored "Cosmic Impressions", with the introduction of Cardinal Franz König on the relation between Science and Religion. In that book he sums up his feelings about the scientific discoveries made by modern cosmology: "In the last decades, new worlds have been unveiled that our great teachers wouldn't have even dreamed of. The panorama of cosmic evolution now enables deep insights into the blueprint of creation... Human beings recognize the blueprints, and understand the language of the Creator... These realizations do not make science the enemy of religion, but glorify the book of Genesis in the Bible".

Thirring was also a music composer and played the organ. In his biography he wrote: "Music is a subject that one cannot clarify through physics concepts".

Throughout his life he received numerous awards such as the Erwin Schrödinger Prize, the Max Planck Medal, and the Henri Poincaré Prize.

In addition to being a member of our Pontifical Academy of Sciences he was also a member of the Austrian Academy of Sciences, the German Academy of Sciences Leopoldina, the National Academy of Sciences, USA, the Academia Europaea, and of the Hungarian Academy of Sciences. He held an Honorary doctorate from the Comenius University in Bratislava (1994).

He received many honors: Eötvös Medal (1967); Erwin Schrödinger Prize (1969); Max Planck Medal of the German Physical Society (1978); Prize of the city of Vienna (1978); Austrian Decoration for Science and Art (1993); Honorary Medal of the Austrian capital Vienna in Gold (1993); Honorary doctorate from the Comenius University in Bratislava (1994); Henri Poincaré Prize of IAMP (International Association of Mathematical Physics) 200.

His memory will be respectfully remembered by all of us.

CARLO RUBBIA

Alexander Rich († 27.IV.2015)

I have the honour to commemorate our highly estimated academician Alexander Rich. He died on 27 April 2015 at the age of 90 years. He grew up in the United States of America (USA), where he also obtained his basic scientific education. He started his scientific research under the mentorship of Linus Pauling, and in close contact with James Watson and Francis Crick in structural biology. From 1958 he had a professorship in biophysics at the Massachusetts Institute of Technology (MIT) and at the Harvard Medical School (HMS). Alexander Rich devoted his research mainly to the structural and functional analysis of nucleic acids, both DNA and RNA. These investigations revealed various alternative forms of these principally filamentous molecules, often in connection with interacting proteins. This allowed Rich to explore specific biological functions, for example of Z-DNA in its interaction with regulating proteins. The publication list of Alexander Rich contains a large number of highly valuable reports on research accomplished under his direction. On the basis of his scientific accomplishments, Alexander Rich became member of the Pontifical Academies of Sciences (PAS) in 1978. As Academician he made important scientific contributions both to our Plenary Sessions and to our topical workshops. The Academy also appreciates his fundamental help in the elaboration of conclusions and recommendations during our scientific meetings. The Pontifical Academies of Sciences (PAS) owes its sincere thanks to its defunct member.

Werner Arber

Charles Hard Townes († 27.I.2015)

It is a great honor for me to present this commemoration of Charles Hard Townes. Charlie, as he was known to everyone, was one of my personal and scientific heroes. He was a man of science and a man of faith; a Nobel laureate and a public servant; and for me a teacher and a friend. He deeply changed both the science and technology of the 20th century. As inventor of the maser and laser, he introduced a device so ubiquitous to modern society that it is hard to imagine either scientific research or daily life without it. In astrophysics, he discovered the first triatomic molecules in deep space and he found evidence for the black hole at the center of our galaxy.

Charlie was born in Greenville, North Carolina. After finishing high school at the age of 15, he attended Furman University in his hometown, graduating in 1935. He got a master's degree from Duke university and a PHD from Caltech in 1939. He then joined the staff of Bell Labs, where he worked on the development of radar, a key technology for the Allies in World War II. That experience set the stage for his work on microwave spectroscopy of molecules that led to the 1955 book co-authored with Art Schawlow, entitled simply "Microwave Spectroscopy". It was one of the first books that I studied when I began my research career as an undergraduate at Juniata College. In 1948, Charlie went to Columbia University and continued to work on microwaves.

Searching for microwaves sources working at ever-higher frequencies, he developed the concept of the maser, an acronym for Microwave Amplification by Stimulated Emission of Radiation. Among the key ideas that made the maser a reality, was a resonant cavity, which stored and built up the stimulated microwave field. Famously, the idea for that came to Charlie during an early morning outing while he was sitting on a bench in Washington DC in 1951. It was in that same year that he married Frances

Figure 1. Charlie and Frances Townes on the bench in New York City commemorating his inspired idea leading to a successful MASER.

Brown. He is shown with her here (see Fig. 1), sitting on a bench that was built many years later to commemorate that inspirational moment. Charlie and his young colleagues reported operating the first maser and here (see Fig. 2) Charlie is shown with Jim Gordon in front of that maser.

A few years later, in 1958, Charlie and Art Schawlow, who was also his brother-in-law, extended the idea of the maser to optical frequencies, coming up with the laser. Their idea was that the gain medium was now inside the mirrors of a Fabry-Pérot Cavity. In 1960, the first laser was made by Ted Maiman, and in 1964 Townes shared the Nobel Prize in Physics with Basov and Prokhorov who had independently come up with similar ideas. As the father of the laser, Townes' influence on science and technology cannot be overstated. Today, essentially everyone relies on lasers for a wide variety of applications that range from scientific research, to communication, data storage, and medical procedures.

After serving as an advisor to the US government for a few years, a role he played a number of times in his career, Charlie moved to MIT as the

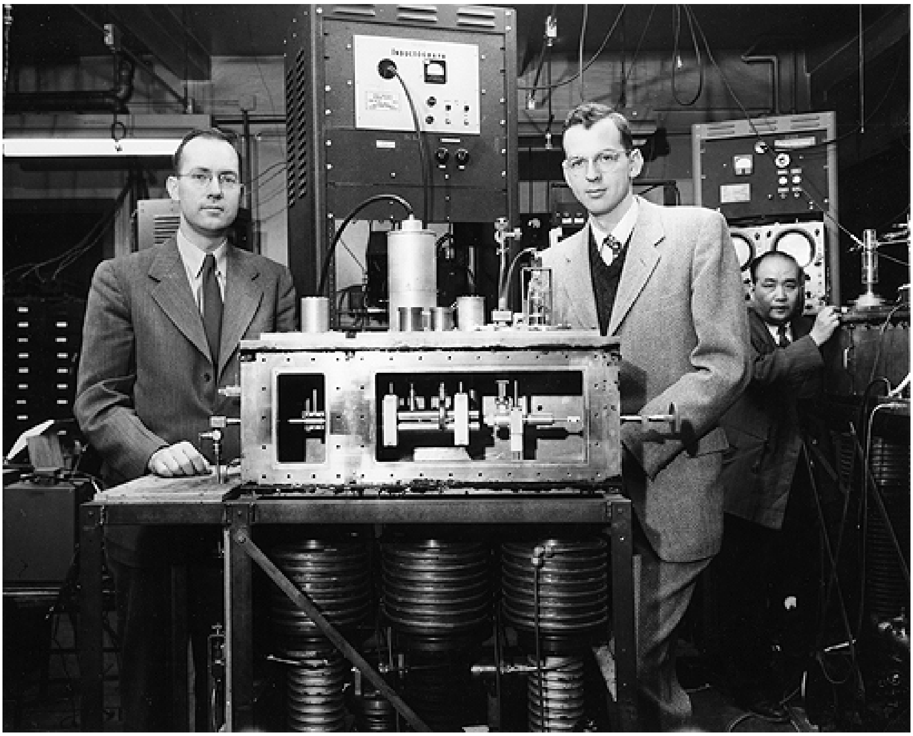


Figure 2. Charlie Townes (left) with Jim Gordon (right) and the first MASER.

provost, and it was while he was at MIT that he received the Nobel Prize. In 1967, he returned to basic research as a professor at the University of California at Berkley, pursuing interests in radio astronomy and astrophysics.

Charlie's change in research direction at such a late stage of his career was both impressive and productive. At a time when most people thought that the most complicated molecules in interstellar space were a few diatomic species, Charlie discovered ammonia and water, the first triatomics discovered in deep space. He pioneered mid-infrared astronomical interferometry; he made the first heterodyne spectrometer, and in the 1980s, using precision spectroscopy techniques, he identified the black hole at the center of the Milky Way galaxy, a feature that had been predicted by Martin Rees.

Charlie's enthusiasm and hands-on approach to research never faded. Although he was officially retired in 1986, over 20 years later, in his nine-

Figure 3. Charlie Townes cleaning a telescope mirror.

ties, he could be found, as you see in this photograph (see Fig. 3), perched on a telescope mount, preparing the mirror for a night of observing by dusting off the surface.

Charlie was also a pioneer in the connection between science and religion. He was an important mentor to me and to others interested in this subject. In 1964, at the famous Riverside Church in New York City, where he was a member, Charlie gave a talk that became a 1966 published article, entitled 'The convergence of science and religion'. This was a landmark in the field of science and religion. I see it as the beginning of the modern study of science and religion, and its wide influence was a major factor in Charlie's receiving the 2005 Templeton Prize "for progress toward research or discoveries about spiritual realities". He was the first, and I believe the only person to receive both a Nobel Prize and a Templeton Prize.

I spoke with Art Schawlow, Charlie's collaborator on the invention of the laser, shortly before Art's death, and Art told me a story about how someone had characterized another prominent physicist as "the smartest person he knew". Art's response was, "not while Charlie Townes is alive". Charlie died just 6 months before his 100th birthday, leaving us richer for all that he did.

William D. Phillips

Card. Georges M.M. Cottier († 31.III.2016)

Dans la fresque qui orne le grand mur de la salle du chapitre du couvent Saint-Marc de Florence, Fra Angelico a représenté saint Dominique. Il a placé son visage au centre d'un déploiement d'autres visages reliés par une branche qui comme celle de vigne se déploie largement dans l'espace. Ainsi Fra Angelico a exprimé le lien vital entre le fondateur de l'Ordre des prêcheurs et ses fils spirituels donnés en exemple à la communauté qui se réunit en cette salle. Le large panneau de fresque donne à voir les figures des plus éminents parmi les serviteurs de l'Église. On y voit deux papes, plusieurs cardinaux, patriarches et évêques, quelques grands théologiens et prédicateurs honorés au quattrocento en Italie. Le mouvement pourrait s'étendre… et sans aucun doute la fresque porterait le visage de notre confrère le cardinal Georges Cottier avec le titre de " théologien de la maison pontificale ". Cette fonction, traditionnellement réservée aux Dominicains. Son exercice implique une grande discrétion – sur ce point, Georges Cottier fut exemplaire. Il n'était pas de ceux qui se laissaient faire par les journalistes curieux de quelques informations d'autant plus intéressantes qu'entourées du secret. Non, il accomplissait sa tâche avec application et discrétion. Pourquoi mentionner dès l'entrée cette fonction sur laquelle je n'ai rien à dire, sinon parce qu'elle représente un point nodal pour comprendre l'unité et la fécondité d'une vie.

Georges Cottier était suisse. Ce petit pays au centre de l'Europe est connu pour sa neutralité dans les guerres qui ont ravagé l'Europe, pour sa stabilité politique et sa richesse liée à un système bancaire international. On omet souvent de reconnaître qu'étant multilinguistique, selon une organisation fédérale bien réglée, il est un lieu de passage entre les cultures des grands ensembles européens et tout particulièrement pour ce qui relève de la rencontre entre les traditions latine, italienne ou française et germanique : une vocation à la paix dans les terribles guerres qui ont des motifs politiques, économiques mais aussi et d'abord culturelles. Georges Cottier né le 25 avril 1922 a été étudiant en lettres à l'époque où la Suisse était témoin de l'essor des totalitarismes européens. Il a connu les cercles d'étudiants marqués par l'influence de celui qui était alors l'abbé Journet, grand théologien de l'Église par la suite, ami du pape Paul VI, cardinal. Dans ces cercles, face au nazisme, la neutralité officielle du gouvernement suisse n'était pas acceptée dans la mesure où elle devenait une caution, voire une complicité, avec les méfaits de l'emprise du nazisme sur le monde germanique. Cet esprit de résistance passait par des actions de solidarité. Pendant la guerre, bien des résistants français bénéficiaires de ces réseaux dont le centre était à Genève. La résistance au totalitarisme ne concernait pas seulement le Nazisme ; elle concernait aussi le communisme dirigé par Staline. C'est dans ce souci de lutte pour la liberté, que Georges Cottier prit comme sujet de thèse pour son doctorat la pensée de Karl Marx. Sa thèse, publiée sous le titre Du romantisme au marxisme, était novatrice dans le monde de la pensée ; elle allait à la source et elle était plus profonde que les études universitaires classiques, tant celle des marxistes que de leurs adversaires. Cette thèse n'était pas seulement une exégèse des textes de Marx, elle en relevait la genèse et plaçait sa réflexion dans l'ensemble du mouvement de la pensée européenne. Une porte s'ouvrait pour une autre compréhension des racines et des enjeux des drames liés aux totalitarismes en quête de la domination du monde.

Après la guerre, G. Cottier entra dans l'ordre des Dominicains. Il fut formé à Paris, dans cette ville bouillonnante d'initiatives dans une Europe en reconstruction et où jésuites et dominicains ouvraient les voies qui furent au cœur du Concile Vatican II. Il y connut un " thomisme ouvert ".

Il revint ensuite en Suisse pour fonder un couvent dans l'agglomération de Genève ; il se fixa ensuite à Fribourg professeur de philosophie, chargé maître ès pensée allemande et française. Ses compétences philosophiques firent de lui un expert auprès du pape Paul VI dans le souci de la paix. Georges Cottier fut un des intellectuels engagés dans le dialogue avec les divers athéismes dans le cadre du Conseil Pontifical pour les Incroyants. Il participa à de très nombreuses conférences internationales, comme expert. Sa démarche érudite était rigoureuse et lucide sur l', tout à la fois ouverte et sans concession. En 1989, il fut nommé " théologien de la maison pontificale " par le pape Jean-Paul II. Cette nomination marquait une rupture avec le thomisme étroit de son prédécesseur à ce poste. Georges Cottier était dans la tradition de Jacques Maritain et des Pères conciliaires, en particulier sur le point décisif de la liberté de conscience. Je ne présenterai pas ici ses travaux théologiques ni ses publications en ce domaine, car elles ne concernent pas directement le monde de la science, objet de nos études académiques. Un point mérite d'être relevé. La théologie de Georges Cottier s'inscrit dans la compréhension du salut développée par saint Thomas d'Aquin : le don de Dieu et sa présence (la grâce) n'abolit ni de détruit la nature, elle l'accomplit. Il en résulte une quête d'unité et d'harmonie entre les savoirs.

Un autre point me semble important à relever dans le cadre de nos travaux. La référence à saint Thomas n'est pas étrangère à la présence de Georges Cottier à l'Académie Pontificale des Sciences. Pour lui, Thomas d'Aquin représente un modèle pour le rapport avec les sciences de la nature. Nul n'ignore que la pensée chrétienne latine a été influencée par saint Augustin. Celui-ci a entraîné la philosophie dans une perspective spiritualiste, voire dualiste. Albert le Grand puis Thomas d'Aquin ont redécouvert Aristote, philosophe qui fondait la démarche philosophique sur les sciences de la nature. Thomas d'Aquin a lu et commenté les œuvres scientifiques d'Aristote – en premier lieu les traités concernant les vivants. Dans l'école thomiste, les données des sciences de la nature doivent être reçues comme un fondement. Aussi les bouleversements dans les connaissances scientifiques doivent être l'occasion d'un renouvellement de la théologie et même d'un approfondissement. Cette tâche n'est pas facile. Georges Cottier l'a mené avec rigueur, prudence et audace. Ainsi lors de la publication de l'encyclique Humanae Vitae, Georges Cottier a manifesté son désaccord sur certains points de l'argumentation pontificale – qui effectivement ne correspond pas à la manière dont saint Thomas articule le "naturel" et l'"artificiel". Georges Cottier fit partie de ceux qui refusèrent que l'encyclique de Paul VI soit considérée comme une déclaration doctrinale infaillible – ce qui ne réduit en rien la valeur de la doctrine traditionnelle du mariage comme sacrement, au contraire. Ainsi Georges Cottier est-il une figure de liberté dans la réflexion philosophique et théologique – cette liberté qui est le fruit de l'érudition et de la finesse de l'intelligence qui pénètre à l'intime du réel et l'ouvre sur le mystère de la création et de la vocation humaine à l'éternité. Georges Cottier fut et restera un modèle de liberté de pensée, selon l'idéal de notre Académie.

Jean-Michel Maldamé

Ahmed Hassan Zewail († 2.VIII.2016)

Professor Ahmed Hassan Zewail, Linus Pauli Professor at the California Institute of Technology (Caltech), passed away on August 2, 2016 at his home near Pasadena, California, after losing a battle with cancer.

Ahmed Zewail was awarded the 1999 Nobel Prize in Chemistry as the sole winner for his pioneering work on ultrafast chemistry. He became the first science Nobel Prize winner from the Arabic-speaking world. As a native Egyptian, he was honored with the Order of the Nile, the highest honor the State of Egypt can bestow, and received a military funeral in his native country.

In his research, he employed ultrashort laser pulses to develop stroboscopic pump-probe techniques on a femtosecond time scale. In this way, he made it possible to observe the extremely fast dynamics of molecular matter in slow motion and to study elementary processes in complex systems, including bio-molecules. With a shutter time a million times faster than ordinary cameras, it becomes possible to capture the motion of atoms and to resolve transient states during chemical reactions. The observation of such phenomena and the development of appropriate models has led to a deeper understanding of the motion and forces in the microcosm of atoms and molecules, with applications ranging from quantum chemistry to molecular biology. His impressively elegant experiments revealed the important role of coherence much beyond what had long been assumed. With the creation of the new field femtochemistry, Ahmed Zewail has left a towering scientific legacy that will inspire many future discoveries. More recently, Professor Zewail and his team pioneered the powerful technique of 4D microscopy that uses diffraction of ultrafast pulses of electrons to track reactions in space and time on the atomic scale.

Professor Zewail is author of the autobiography Voyage Through Time: Walks of Life to the Nobel Prize that reveals in a very personal style his approach to science and life, motivating aspiring young people from around the world to enter the world of science.

Ahmed Zewail was born in Damanhur, Egypt, on February 26, 1946, as the oldest child of a middle-class family. He grew up in Desouk, Egypt, a small town 80 km from Alexandria. He received his bachelor's and masters' degrees from Alexandria University. With a teaching fellowship he moved to the USA to pursue doctoral research with Robin Hochstrasser at the University of Pennsylvania. Working on novel spectroscopies, including optically detected magnetic resonance, he completed his doctorate in 1974. After graduating, he came to California to pursue postdoctoral research on coherence and energy transfer in solids with Charles B. Harris at UC Berkeley. In 1976 he joined the faculty of the California Institute of Technology in Pasadena, and he remained there for the rest of his career. At Caltech, he became the director of the Physical Biology Center for Ultrafast Science and Technology and was named the Linus Pauling Professor of Chemistry in 1995.

It is a privilege for me to have known Ahmed Zewail as a personal friend and an esteemed colleague for more than four decades, ever since I worked as a young Professor at Stanford University. During all this time, I admired his brilliant scientific insights, his elegant experiments, his creative vision, boundless energy and contagious enthusiasm. I was thrilled when we shared the King Faisal International Prize in Science in 1989.

Since then, Ahmed Zewail received countless other prizes and honors. His unique list of distinction includes early prestigious prizes such as the Wolf Prize in Chemistry (1993), the Robert Welch Prize in Chemistry (1997) and the Franklin Medal (1998). Ahmed Zewail was a member, foreign member, or honorary member of many Societies and Academies, including the US National Academy of Sciences, the American Academy of Arts and Sciences, the American Philosophical Society, the Pontifical Academy of Sciences, the Royal Danish Society of Science and Letters, the American Association for the Advancement of Science, the Chemical Society of India, the Royal Society of London, the Indian Academy of Sciences, the Russian Academy of Science, the Royal Swedish Academy of Science, and the Royal Academy of Belgium. He was honored with countless honorary doctorates, including degrees from Heriot Watt University, Lund University, Cambridge University, Complutense University, University of Jordan, University of Glasgow, and Yale University, Ahmed Zewail was not only a brilliant scientist, but also an exceptionally passionate and influential diplomat and Academic Statesman, who used his stature to advance science and science education in Egypt and the Arabic-speaking world. In 1999, he proposed a new center of learning and research in Egypt with the ambition to become the Caltech of the Middle-East. This center was inaugurated in Giza, 30 km outside Cairo, one year later, and named in his honor "Zewail City of Science and Technology". I have been honored to serve on the Supreme Advisory Board of Zewail City of Science and Technology since its inception and I am happy to see that Zewail City has begun to grow and flourish despite all the political upheavals in the region. It will add to the lasting legacy of Ahmed Zewail. With his passing, the world is losing a towering scientist, an exceptional statesman, and a passionate human being.

Professor Ahmed Zewail is survived by his wife, Dema Faham, and four children, Maha, Amani, Nabeel, and Hani.

THEODOR W. HÄNSCH

Raymond Hide († 6.IX.2016)

Raymond Hide was a specialist in the dynamics of fluids. He achieved important insights into meteorology and planetary atmospheres. He also studied the Earth's magnetic field – showing how it was generated by convective motions in its electrically-conducting liquid core, and how similar processes could operate in the Sun and other planets. He achieved his insights by a mixture of mathematical modelling and ingenious laboratory experiments.

Raymond was born in 1929, in a coal-mining village in Yorkshire. He attended the local Grammar School, and then gained a scholarship to study physics at the University of Manchester. Here he was lucky to be mentored by the great physicist Patrick Blackett. Blackett had become interested in understanding why the Earth, the Sun and other cosmic bodies had magnetic fields. He made a radical conjecture that there was a new fundamental law whereby gravitating bodies would get magnetised if they were spinning. This simple law relating gravity and spin was testable on the Earth because it would have implied that deep inside the Earth the field would be weaker. Blackett, along with Keith Runcorn, later to become a distinguished geophysicist, decided to test this prediction by making measurements down a mineshaft.

Raymond went along as their research assistant. The magnetic field deep down turned out to be stronger – refuting this theory. This introduction to science and its methodology had a formative and inspirational impact on Raymond.

He decided, for his PhD, to explore more complicated ways in which rotating objects get magnetised. And he became a pioneer of the now-accepted theory that in a conducting fluid (like the Earth's molten interior, or the ionized gas that the Sun is made of) convective motions could generate magnetic fields by a kind of dynamo action.

His PhD thesis was a classic. He tried to simulate the kind of convective motions that could occur in gravitating fluids by a very simple experiment. It involved two vertical glass cylinders, one inside the other. Water was placed in the annulus between them. The cylinders were spun, so that centrifugal force mimicked gravity. And the outer cylinder was kept hot, the inner one cold. This radial temperature gradient would induce convection, as inside the earth or a star.

As the spin rate increased he found a transition from a regular pattern to periodic fluctuations (which he called vacillation) and ultimately to chaotic behaviour.

These experiments were motivated by attempts to understand the Earth's interior. But Raymond realised that they were relevant to atmospheric circulation, and their ramifications motivated much of his subsequent research.

He spent a postdoctoral year working with Chandrasekhar in Chicago, followed by three years National Service back in the UK, And then a Lectureship at Newcastle, where Runcorn was now Professor. While there he further developed models for the Earth's magnetic field, and also became an expert on the dynamics of terrestrial and planetary atmospheres. And he found a fluid-mechanical explanation of something that had long fascinated him – the stable long-lived feature on Jupiter known as the Great Red Spot.

Raymond moved to the USA in 1961 as a Professor at MIT but after six years he came back to the British Meteorological Office. There he headed a Geophysical Fluid Dynamics Laboratory where he could do more elaborate experiments – for instance repeating his PhD experiment but with an electrolyte instead of water, to study magnetic effects. Meanwhile, he had extended his interest into planetary interiors. He also explored how motions in the Earth's liquid core distorted the core-mantle interface, and the consequential changes in the Earth's rotation and in the length of day.

He and his group later moved to Oxford, to work at what later became the Hooke Institute, and became a Fellow at Jesus College. After he had officially retired in 1992, he took up various visiting positions before settling in the Department of Mathematics at Imperial College, London.

He continued to work on the Earth's dynamo, and the way regular behaviour can become chaotic. By this time, computers had advanced to the stage that numerical experiments could supplement those on real fluids. In helping to understand the Earth's internal dynamo, and the transition from regular to chaotic behaviour. And he showed how the magnetic fields in small bodies in the solar system could be generated by high-velocity impacts.

Raymond's scientific career was celebrated by a festschrift on his 80th birthday in 2009. In his last years he became frail and moved with his wife Ann to a care home, where both passed away within a few months of each other. He was 87 years old.

Raymond became a Fellow of the Royal Society in 1971 and received a CBE from the UK government in 1990, as well as other awards. He served terms, unusually, as president of both the Royal Astronomical Society and the Royal Meteorological Society.

He was elected to the Pontifical Academy of Sciences in 1996. He attended several of our meetings, speaking at four of them – always with clarity, deriving important conclusions about nature from simple models. He was a wonderful companion, and a mentor to generations of younger scientists. May he rest in peace.

MARTIN J. REES

Mambillikalathil G.K. Menon († 22.XI.2016)

A scientist statesman and a dear friend

I met Professor M.G.K. Menon (Goku) for the first time around 50 years ago in a meeting of the Indian Academy of Sciences. That was the period when Prof. C.V. Raman presided over the Academy and gave an evening lecture. The very first time I met Prof. Menon, it became clear to me that I was talking to a brilliant man. He was then Deputy Director and Professor at the Tata Institute of Fundamental Research. Prof. Homi Bhabha chose him personally as the Deputy Director in charge of physical sciences at the TIFR, acknowledging his brilliance and other attributes. He became director of TIFR in 1966 after Prof. Bhabha passed away in a tragic accident. Prof. Menon had created a great scientific record in Bristol (UK), having carried out outstanding research in the group of Professor C.F. Powell on cosmic rays. He had been offered a good faculty position in the US, but he chose to come back to India. Prof. Menon was elected fellow of the Royal Society, London, at a very young age.

Prof. Menon has served the country and the Indian Government in various capacities and with a variety of portfolios. He has been in charge of the space program, CSIR, Department of Environment, Dept. of Electronics, DRDO and Department of Science and Technology at different times. When Mr. V.P. Singh was Prime Minister, Prof. Menon was Minister of Science & Technology. He was member of the Planning Commission and Scientific Adviser to the Indian Government during Rajiv Gandhi's Prime Ministership. I had many opportunities to be in close touch with him from the late seventies and he became a close friend. I started calling him Goku. He was Goku to his friends.

Over the years, I have got to know Prof. Menon in various ways, because of common interests and our involvement in various organizations. When he was the Secretary of the Department of Science and Technology, I worked closely with him on the Science and Engineering Research Council. When I was a member of the National Committee on Science and Technology in the early 1970s, I met him a few times to discuss issues related to science policy.

Our close relationship really started when I visited China in a delegation with Prof. Menon as the leader of the delegation. That was the first Indian delegation to China after the cultural revolution. Our common friend, late Devendra Lal, was with us in the delegation as also A.P Mitra and M.M. Sharma. It was one of the most enjoyable international visits I have had. We went round China visiting institutions and wondering how much better off we were in India in terms of facilities and infrastructure. (Alas! the situation no longer holds).

When I became Director of Indian Institute of Science in 1984, Goku was member of the Planning Commission. Considering the pathetic condition of the 75-year old Institute in terms of basic infrastructure facilities including water and electricity, I approached him for help. He saw to it that a special grant of Rs.3 crores was made available so that the Institute could rectify some serious shortcomings.

We were both members of the Atomic Energy Commission for some years. I looked forward to the lunch in Taj (Mansingh Road) with Goku after the meeting of the Commission. Mr. J.R.D. Tata, who was also a member of the Commission, would often dine with us.

I worked closely with Goku when I was Chairman of the Science Advisory Council to Prime Minister Rajiv Gandhi. We did several things together at that time. Creation of TIFAC was one such happening.

Having known Goku closely for the last thirty or more years, I must say the following. I consider him to be one of the most brilliant people whom I have known. He had an outstanding mind and possessed great clarity of thought. If he had continued purely in science, he would have made major contributions and reached great heights. However, he decided to serve India in various ways. While it was a loss to science and a personal loss to him, the country benefitted considerably. I have often said that Goku was the academic conscience of the scientific community. I considered Satish Dhawan to be the moral conscience of the scientific community.

Goku is the only person that I know who has headed many major agencies and departments of the Government of India and also all the three science academies. He was also involved in the councils of variety of scientific and educational institutions including the Indian Institute of Science, Raman Research Institute, some of the IITs and the Indian Statistical Institute.

I have enjoyed knowing Goku Menon. We think somewhat similarly on issues. We have many common friends as well as common interests. I feel bad that Goku's services have not been fully utilized in the last few years. I am also not sure that he has been properly compensated for the immense contributions made by him.

It is most unfortunate that Goku's health deteriorated during the last several months. I felt terribly sad seeing him that way. I can only think of a cheerful Goku, full of enthusiasm and ideas.

Goku has been a dear friend. He has also been a national treasure.

CHINTAMANI N.R. RAO

Long-Term Responsibility

Jürgen Mittelstraß

1. Bearing responsibility is one of the things that make us human. We take on responsibility in the family, in our profession, and in society. We bear responsibility for people that we meet and for the institutions in which we live. We bear responsibility for the ideas upon which the institutions are based: for instance, for freedom, for justice, for democratic structures. And we bear responsibility for what – beyond our own world, the world that we make – bears us: for Nature – as creating and created nature, *natura naturans* and *natura naturata,* as the Ancients said. In Aristotelian physics nature was always *natura naturans*; in Plato's cosmology *natura naturata* was made by a powerful demiurge, who was to become the Creator in Christian thought. In as much as we bear responsibility – here for the world – we also take on obligations.

Responsibility and the obligations that ensue upon it are not limited to the respective present. This distinguishes it from that kind of responsibility, which we assume only temporarily for an action and from obligations that end with an accomplished purpose. These are long-term, and, if we think in generations, they involve future generations, especially their conditions of life. When we mean this kind of responsibility and these kinds of obligations, we speak of *long-term responsibility*. What makes this so special? – And what makes it a problem when we think about it more rigorously? The answer is simple. Thinking two or three generations ahead, be that in individual or institutional relations, is still very concrete, and we can reckon with constant environmental conditions. By contrast, thinking more than two or three generations ahead, or even skipping over a chain of generations into future centuries is abstract; we must assume relations that are unknown and cannot be predicted. Two aspects should be emphasized.

First: In the case of long-term responsibility, the obligations that are entered into with this responsibility do not stop at a particular generation. A thought experiment can make this clear.[1] Suppose that there are rights

[1]The thought experiment of H. Hofmann (*Rechtsfragen der atomaren Entsorgung* Stuttgart: Klett-Cotta 1981, pp. 267ff.) is cited as summarized by C.F. Gethmann, "Langzeitverantwortung als ethisches Problem im Umweltstaat", in: C.F. Gethmann *et al.*, *Langzeitverantwortung im Umweltstaat*, Bonn: Economica-Verlag, 1993, p. 9.

(whatever their content) that we recognize for *all* humans: can this recognition be taken to be time-limited and valid only up to a generation *k*? On the assumption that certain rights, for instance, the basic human rights, are taken to be time-limited up to generation *k*, then it would follow that the generation *k*+1 is denied these rights, and thus there would be people whose rights must be denied. This consequence would contradict the assumption that there are rights that apply to all. But human rights do not expire. There is thus no generation at which the extension of the obligation, for instance, the preservation of human rights, ends; thus, some obligations are unlimited. In other words: The termination of a long-term responsibility would be an arbitrary decision and would violate the principle of *ethical universalism*. This is accepted by more or less all ethical systems, in particular by obligation ethics such as the ethics of Immanuel Kant with its categorical imperative. In ethical universalism, a common will to consider one another in actions as ends in themselves and not merely as means to particular ends is assumed (even counterfactually).[2] This includes future generations.

Secondly: Assuming the existence of an unlimited (unlimitable) long-term responsibility, the question arises, whether such a responsibility exists in the same way and in same measure with regard to all generations. This is not the case. The reason is that we do not know what the life-world of a future generation *k* will be like. We therefore do not know what we should do or not do in regard to that generation. We know this in regard to the generations that share, or foreseeably will share, our life situation; the generations of our children and grandchildren. Thus the obligations with regard to distant future generations cannot be the same as with regard to near generations. Or in other words: "the binding character of an obligation regarding temporally closer generations should be weighted more heavily in comparison to those regarding more distant generations"[3] without thereby violating principles of an ethical universalism.

Assuming even minimal anthropological constants, there are still some elementary obligations towards distant future generations that can be identified. Among these are precautionary care for clean water, healthful nourishment, stable conditions of reproduction, energy, biological and cultural

[2]See F. Kambartel, "Universalitaet (ethisch)", in: J. Mittelstraß (ed.), *Enzyklopaedie Philosophie und Wissenschaftstheorie,* vol. IV, Stuttgart: Metzler, 1996, pp. 414-415.

[3]C.F. Gethmann, "Wer ist der Adressat der Langzeitverpflichtung?", in: C.F. Gethmann and J. Mittelstraß (eds.), *Langzeitverantwortung: Ethik Technik Oekologie*, Darmstadt: Wissenschaftliche Buchgesellschaft, 2008, p. 14.

variety. Thus in the case of securing sufficient energy resources, we must avoid an irreversible exhaustion of raw materials, and therefore energy research which keeps open all options, including nuclear energy, and an economy of resources that deals carefully with non-replaceable raw materials belong to the most important tasks of humanity with regard to future generations. This includes also the securing of sufficient research resources, for example, in solar research and research on nuclear fusion.

The same applies to danger prevention that affects both current and future generations. One example is climate research, that is not driven only by a scientific knowledge-interest but also by tangible problems whose solutions are of existential importance for both those living now and, to a much more dramatic extent, for future generations. This does not presuppose a more exact knowledge of the life conditions of these generations. What is important is only that the life spaces of future generations or the corresponding options are not restricted in an irreversible manner (keyword: rational economy of resources and preservation of biodiversity, that is, diversity of species, genetic diversity, and diversity of ecosystems). This holds as well for purportedly simple precautions such as safeguarding and marking dangerous waste repositories. The question is, for instance, how the supervision of repositories for highly radioactive nuclear waste can be assured for the next thousand years, whereby it may be assumed that the appropriate documentation and its observance cannot be dependably guaranteed for more than hundred years. In general: Precisely by every generation's doing the obvious, that is, passing on the earth to the next generation as they themselves found it, perhaps even a little better and more stable, they will secure the future of humankind for an incalculable time and comply with their responsibility in the sense of long-term responsibility as well.

2. The problems of a long-term responsibility are discussed today using the concepts of *sustainability* and *intergenerational justice*. The concept of *sustainability* dominates the environmental discussion, and the concept of *intergenerational justice* dominates political rhetoric. Both concepts deal implicitly with long-term responsibility even though these concepts are not at all clear from the start – and even increasingly lose what clarity they had.[4] Thus, the concept of sustainability is meanwhile used in a downright

[4]See C.F. Gethmann and J. Mittelstraß, *Langzeitverantwortung* (see footnote 3), pp. 7-8. See also, for a long lasting debate, D. Birnbacher, *Verantwortung fuer zukuenftige Generationen*, Stuttgart: Reclam 1988; D.P. Callahan, "What Obligations Do We Have to

inflationary manner. Compared to its original meaning in forestry (the obligation to plant saplings to replace felled trees) this concept, especially when used simply in the sense of 'enduring', has to a large extent lost its authentic meaning. Sustainability is demanded everywhere, for instance, in entrepreneurship, in the construction industry, in financial policy, in the areas of health and energy. It is hard to understand what sustainable health care, sustainable energy consumption is supposed to be. The precise meaning of the concept of sustainability dissolves itself to a large extent in an increasingly metaphorical use, which simply means lastingness.

The same applies to the concept of intergenerational justice. This deals with a real exchange relation between generations that stand in direct connection with one another; when applied to distant generations, it loses its meaning (no questions of distribution are raised here, but rather only questions of predictability and of the consequences of present decisions for distant generations). Hence, in both the case of the concept of sustainability and the concept of intergenerational justice, the real *normative* meaning, which is given with the concept of long-term responsibility, is pushed into the background although the point is precisely to take responsibility and to enter into the corresponding obligations. We could then recommend replacing the two concepts with the concept of long-term responsibility. For the issue is not primarily one of economic and ecological questions, the answer to which is rather a means to an end. This end becomes concrete in an ethics of long-term responsibility.

3. Science, which deliberately takes on tasks of responsibility and the corresponding obligations, assumes a *moral form* and becomes a moral subject. This seems to collide with a principle that, within science and with regard to science, is called the principle of *value freedom* and has been held to be a constitutive principle of scientific work as such ever since the sociologist Max Weber. According to Weber, normative foundational efforts in scientific theory formation are inevitably ideological, and at the same time the scientific character of such work can be defined without recourse to normative elements.[5] Science, according to this principle, would be – free

Future Generations?" in: E. Partridge (ed.), *Responsibilities to Future Generations. Environmental Ethics*, Buffalo N.Y.: Prometheus Books, pp. 73-85; M.P. Golding, "Obligations to Future Generations", *The Monist* 56 (1972), pp. 85-99.

[5]See M. Weber, *Gesammelte Aufsaetze zur Wissenschaftslehre*, ed. J. Winckelmann, 3rd edition, Tuebingen: Mohr, 1968, pp. 601-602.

of normative limitations – committed solely to ascertaining facts. This presumably excludes moral aspects as well, such as those that are given with the concept of responsibility.

Now freedom and responsibility are difficult concepts, not just in the context of science and research.[6] Hence, the concept of responsibility, in the opinion of many scientists, belongs to the vocabulary of the unfree. But this is mistaken. Freedom, rightly understood, is always *responsible* freedom; otherwise it is arbitrariness. Wherever a claim is made to freedom of research and science, this freedom must be related to structures of responsibility. There are two reasons for this. First of all: science bears responsibility towards itself for maintaining scientific standards. Among these standards are such norms as testability, reproducibility, and credibility. These norms are not merely methodological in nature, they are also *ethical*. Secondly, science bears responsibility with regard to society – for two reasons: because of the essential uncontrollability of scientific knowledge by extra-scientific knowledge, and because of the dependence of modern society on the special competence of the scientific understanding. Connecting up to what has been said about long-term responsibility, this is at the same time a responsibility and an obligation to humanity as a whole.

This responsibility holds with respect to institutions and to individuals. With regard to institutions it holds to the extent that science as a whole takes up long-term responsibility, and with regard to individuals it holds to the extent that the individual scientist is involved. The point here is the *ethos* of science and of the scientist, and thus we have to do with the moral form of science. *Ethos* is to be understood as a living form in which an institution (here science) and the individual (here the scientist) enter into normative relations (here norms of responsibility and the corresponding obligations). This can, in the rightly understood sense of a long-term responsibility directed towards science, be formulated as a *research imperative* or *commandment*: *Let yourself be guided by the thirst for the new and the will to know what innermost holds the world together, but remember that it is no lesser goal to hold that world together with what you do in research and development.*

[6]See J. Mittelstraß, "The Moral Substance of Science", in: *The Cultural Values of Science* (*Proceedings of the Plenary Session 8-11 November 2002*), Vatican City, 2008 (*Pontificiae Academiae Scientiarum Scripta Varia* 105), pp. 179-187.

NEUROSCIENCES AND SCIENTIFIC EDUCATION SESSION

Educating for Sustainable Development & Climate Change: a Challenge for Science Academies

Pierre Léna

Introduction

The future of the Earth's climate, hence of humans beings, is becoming today a central issue in science, in economics, in politics, and even in ethics. Mitigating the global warming, adapting to its worse consequences, designing new ways of living, consuming, producing food and energy are subjects of considerable research, analysis, policies and actions. Climatology was born of 'hard' sciences, such as physics, chemistry, Earth sciences, biology, oceanography, geology, astronomy, indeed mathematics and computer science: it has developed as an interdisciplinary field mixing all these disciplines. More recently, the potential impact of climate changes on human societies and on the fate of individuals has required the involvement of social sciences, extending the interdisciplinarity. Finally, the magnitude of the risks encountered by present humanity and future generations, as well as the necessity to invent a new relation between humans and nature, introduced anthropology and ethics. Entering the *Anthropocene*, to use the term coined by Paul Crutzen, is a great mutation in the course of history.

My contribution aims at stressing the importance of education to prepare and accompany this mutation. The 1946 call by Albert Einstein, initially on the risk of a nuclear war, may well apply today: *A new type of thinking is essential if mankind is to survive and move to higher levels.*[1] Education is the way societies have built to transmit the knowledge of the past, but also to prepare the young generation for the challenges of the future. Adults of tomorrow are today in schools, and they are the ones who will live in the whole 21st century, bearing its evils but possibly being agents of change.

The concern has recently emerged for education as a way to cope with climate change. We analyze here this emergence, what this concern may mean, and how *new types of thinking* could be implemented worldwide in primary and secondary schools, as well as in higher education, to better prepare youth for its future.

1. A recent surge of concern

It is well known that the influence of atmospheric carbon dioxide on Earth's temperature, hence climate, dates back (publications from 1896 to 1903) to the Swedish scientist Svante Arrhenius (1857-1927). After refinements in models and in the physics of the problem, the American Jule Gregory Charney (1917-1981) chaired a Committee of the National Research Council (USA), which in 1979 established a relation between the rate of CO_2 increase and induced temperature rise: although refined, the 1979 prediction remains essentially valid. Eight years later, the Vostok ice drilling in Antarctica produced evidence of the role of insolation changes and established the positive feedback of greenhouse gases on climate. The Intergovernmental Panel on Climate Change (IPCC) was created in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) *to provide policymakers with regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation*. Successive IPCC reports and Conferences of the Parties (COP) increased public and political visibility of climate matters, while the diagnosis remained stable, reaching a constantly increased accuracy (e.g. deciphering the role of clouds and aerosols). A combination of powerful numerical modeling and data collection led to an improved and much more precise attribution of the observed global effects (sea level rise, ocean acidification, arctic ice melting) to global warming, due to greenhouse gases (mostly CO_2, CH_4 and N_2O, H_2O having a different equilibrium regime) and their dominant anthropogenic increase. The projections in the future and causal analysis were expressed in terms of likelihood, translated into more precise degrees of confidence.

In May 2014, when the 5th IPCC Report[2] was finalized, the two Pontifical Academies (Sciences and Social Sciences) organized a Workshop on *Sustainable Humanity, Sustainable Nature, Our Responsibility* where most of planetary the issues were addressed, from physics to social sciences.[3] Nevertheless, the high quality of the work and discussions stopped short of addressing the challenges which climate change, adaptation and mitigation pose to education, despite the obvious conviction of the participants that it was an important and urgent matter. A series of important events were soon to underline this point.

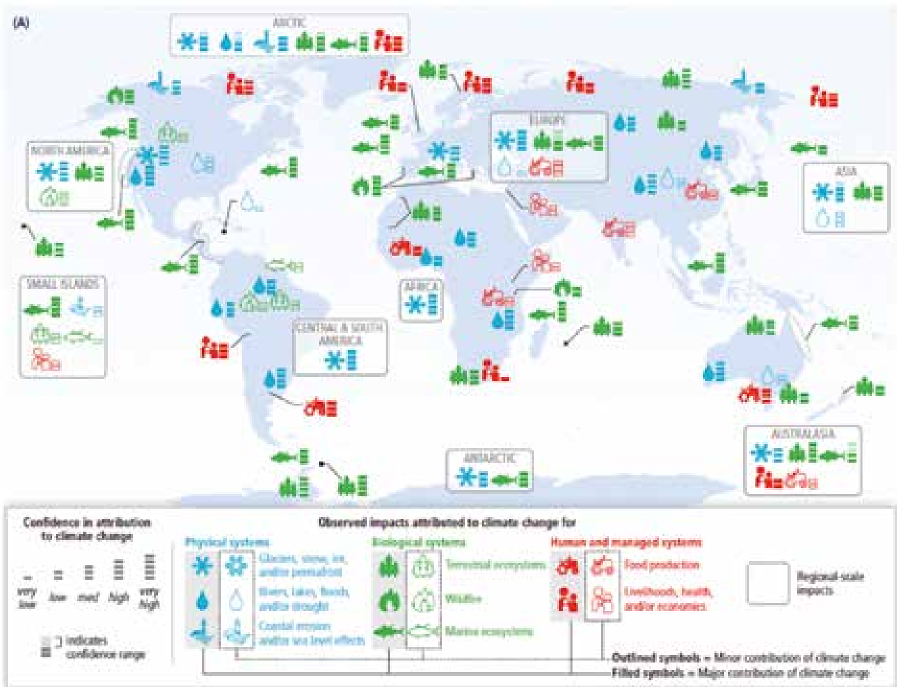
Firstly, just a year later, Pope Francis published his Encyclical Letter *Laudato Si'*, which devotes a full chapter to 'Ecological education and spirituality', pointing to the educational challenge: *Many things have to change course, but it is we human beings above all who need to change. We lack* *an awareness of our common origin, of our mutual belonging, and of a future to be shared with everyone. This basic awareness would enable the development of new convictions, attitudes and forms of life. A great cultural, spiritual and educational challenge stands before us, and it will demand that we set out on the long path of renewal* (6, 202).[4]

Then, in September 2015, the United Nations published the *Sustainable Development Goals*, including education (SDG #4).[5] This synthesis of goals was more specifically accompanied by an inspiring and extensive UNESCO Global Education Monitoring Report (2016), *Education for people and planet: Creating sustainable development for all*.[6]

On December 12 the same year, the 195 national delegations at the Conference of the Parties (COP 21) in Paris signed the *Paris Agreement*, which entered into force after the requested number of ratifications on November 4, 2016. This Agreement addresses education in a specific manner in its Article 12, which reads: '*Parties shall cooperate in taking measures, as appropriate, to enhance climate change education, training, public awareness, public participation and public access to information, recognizing the importance of these steps with respect to enhancing actions under this Agreement*'[7]. The point was already present in the United Nations Framework Convention on Climate Change (UNFCCC, 1992), requesting '*The development and implementation of education and training programmes … in particular for developing countries*' (Art. 6.b.ii).[8] Although the legally compelling aspects of the Paris Agreement remain unclear, its Article 12 is fundamental, since for the signing countries it relates the quantitative goals of the Agreement to a specific action in education.

As climate science is at the heart of the whole process, the scientific community could not stay absent from this new scene of educational challenges. In order to complement its 2014 session and in phase with the COP21, the Pontifical Academy of Sciences organized a specific Workshop in November 2015 on *Children and Sustainable Development: a Challenge for Education*,[9] which began to address the educational challenges for coping with climate change and to gather a series of local actors, from India to California, from Nigeria to France, ready to move into these. At the COP22 in Marrakech (Morocco), several Side Events gave visibility to the matter, including one organized by the Hassan II Academy in Rabat,[10] and several others during the COP itself (IPCC, UNESCO…). In France, the Académie des sciences, jointly with the Agence française de développement, organized a Workshop (Nov. 2016) on *Développement durable, changement climatique et education*,[11] which was concluded by Laurent Fabius, the chief negotiator of the COP21. His passionate plea was to condition the long-term success of the COP21 to a considerable effort in education: *It is necessary that, by a diversity of methods, using the oldest techniques as well as the most recent ones, one reaches a point where the young generation would really understand the phenomenon* [of climate change].[12] And he concluded with a quote by Nelson Mandela: *Education is the most powerful weapon which you can use to change the world, and it is a peaceful weapon.*

This short overview of the last few decades clearly shows a surge of concern. There is decisive progress in the consciousness of the role of education for the future of humanity as a whole, in face of the very real threats of climate change. How then should one proceed? At this point, it appears clearly that climate education, although not explicitly present in the IPCC terms of reference and mandate for action, is requiring some specific analysis, global organisation and actions, in parallel with local initiatives which begin to appear. These will be discussed below.



A global issue: in recent decades, the effects of climate change have been felt in all regions of the world. (Source: *Climate Change 2014 Synthesis Report – Summary for Policymakers*, IPCC).

2. Educating to climate: from understanding to action

The cumulative effect of greenhouse gases in time implies that every delay, measured in years rather than decades, in acting on their production (attenuation/mitigation) makes the next step more difficult, whether it is related to environmental impacts (sea level, ice melting, extreme events..) or societal ones (water availability, food security, climatic refugees…). On the other hand, the timescale for changes in education is usually long, measured in decades rather than in years. This obvious contradiction will not be easily resolved, but this is not a reason for refusing to confront it.

Education will have to make understood and acceptable behavioural changes regarding jobs, energy and water usages, agriculture, transportation, carbon taxes, hence regarding almost all relations which humans have among themselves and with their host planet, fragile and finite. Moreover, the recent notion of climatic justice calls for new solidarities beyond the nation, the region, even the continent, since projections indicate that the ones who will suffer most, if too little is done, are the poorest, often very remote from the ones who contribute most to the climate degradation. On the very positive side, the building-up of decarbonized societies offers opportunities to imagination and entrepreneurship – as did in the past the industrial revolution, the advent of electricity, telephone, nuclear power, medical or pharmaceutical ventures and today digital revolution. All these enterprises were and are calling for science and technical expertise, as well as management, and required an adapted and renewed education.

In the past, some changes at very large scales resulted, when education took the issue seriously. Hygiene offers such an interesting example. In France, between 1850 and 1950, life expectancy at birth increased by 50%, jumping from 40 to 60 years. This was before the discovery and generalisation of antibiotics, and resulted, especially after the discoveries of Louis Pasteur, from long-term actions in elementary schools (primary education became compulsory in France in 1881) as well as within the general public: these actions made perceived and understood the basic scientific contents of hygiene, and the potentially spectacular results of behavioural changes, once people got informed. Indeed one should not forget the 'hygiene-sceptics', who denied the work of the Hungarian physician Ignace Semmelweiss in 1847 in his obstetrician service in Vienna, hence condemning him to a sad death in a psychiatric hospital:[13] 'climate sceptics' are today their equivalent, and education has to convincingly carry the word of science in face of them.

Making climate change understood represents a long way to go, seeming a nearly impossible task. One billion students on Earth receive a mediocre education, and nearly 200 millions do not receive any. In the last five years, 60 millions people increased the number of refugees worldwide, half of them being under the age of 15.[14] At the current rate of schooling, only 14% of children will access secondary education worldwide in 2030. An UNESCO inquiry, analysing the school curricula in 78 countries, showed that only 58% use the term *ecology*, and less than half of them refer to *environmental* topics.6 A majority of adults ignore the causes of climate change, barely understanding the greenhouse effect,[15] even if they are fearful of the future. The observed impact of opinions that deny the anthropogenic origin of the current climate change is a testimony to the ignorance of many people and of their lack of trust in knowledge and scientific reasoning. Even in developed countries such France, teachers in primary and even specialized teachers in secondary schools react more with opinions than with rational analysis.

Youth are somewhat divided when facing climate issues. On one hand, it is easy to witness enthusiasm and generosity in many NGOs (as presented during a recent conference at Erice in Sicily),[16] together with a remarkable presence of young people organisations in the UN-FCCC process and at its Conference of Parties. Emotional reactions, although generous, may not represent a strong enough background for carrying a life-long informed judgement. On the other hand, a recent in-depth analysis of the engagement of young people shows a low level of understanding and responsible conduct.[17] We conclude that a huge and sustained effort is needed to ensure that the younger generations acquire the tools for understanding and for action, forging a *critical and capable mind* to understand and to judge, and a *hopeful heart* – using here the terms proposed by Ramanathan *et al.*[18] – which will be able to build a positive future with solidarity as a beacon. Since it is almost impossible to predict what will be debated and decided in twenty years, the only solution is to empower those who will then be adults with tools that will keep them away from *a priori* thinking, ideologies or irrationality.

3. Specificities of climate education

Let me outline here some of the requisites that a sound climate education should fulfill. We shall focus on secondary education, not forgetting nevertheless the importance of primary school, where some elements could already be conveyed. Higher education would require a dedicated and different analysis.

Climate is undoubtedly an interdisciplinary subject, as it considers the Earth and its inhabitants as a global, complex and highly interdependent system, which cannot be reduced to a specialized, although needed, study. Scientific facts, models and predictions are at the heart of this systemic view, but they are not sufficient: this is well reflected in the IPCC organization into three groups (I for the science, II for the adaptation, III for the attenuation), the latter two involving social and human sciences, as well as climate science and technology. Middle and high schools are not well prepared to deal with such interdisciplinarity: their organisation in separate disciplines, the training and expertise of their teachers, and as mentioned above the present curricula do not naturally facilitate the introduction of climate by taking a systemic approach.

Consequently, practitioners of traditional disciplines, such as physics, chemistry, Earth sciences, life sciences, mathematics, social science and economics, etc., must collaborate in an interdisciplinary manner to address these issues across the curriculum, even at the elementary level. In addition, there is a need to understand how these complex interactions between natural and societal systems (e.g. risk management) connect local actions to global consequences.

Teaching complexity departs from the classical, mostly analytical scheme used to build up knowledge in schools.[19] Yet, in recent times, science has become conscious of the limits of the pure analytical method. The Earth climate system is a beautiful example of this new capability. It requires at least some understanding by the policy makers – leading to the IPCC *Summaries for Policy Makers* – as well as from the average citizen, who in a democratic regime has to exert informed choices – hence the need for education. As expressed by the French sociologist Edgar Morin, *The unability to recognize, address and think the complexity is the result of our educational system* [..], *hence a blindness of intelligence which has invaded all the sectors, technical, political and social ones*.[20]

Teachers have to be introduced to scientific notions, some rather difficult, which are not usually taught in the science courses they receive and escape immediate evidence. Climate studies and conclusions involves multi-factorial causes of phenomena, a great span of space and time scales, randomness, instabilities and phase transitions, non-linearities and feedbacks (positive and negative), a sense of orders of magnitudes, differences between stocks and fluxes, probabilities and projections into the future, etc. Even if these will not be taught in detail in middle school, or even high school, they should be sufficiently approached to retain a scientific content, rather than being reduced to a vague opinion.

Scientific facts and evidences have to be transmitted as knowledge in schools, and accepted as the contribution to the truth built by science.

On the other hand, actions on climate change, whether attenuation or adaptation, are based on political, economic and personal choices which result indeed from rational analysis, but also from values (justice, solidarity at distance and intergenerational) which themselves reflect ethical choices. Beyond communicating scientific facts and reasoning, education there opens the eyes of the students, develops their consciousness, ability to hope, freedom of judgment and choices to act.

Climate science education can build up on the pilot projects, which started two decades ago under the name of *inquiry-based pedagogy*. Inquiry-based pedagogy was initiated by renowned scientists (Georges Charpak, Leon Lederman, Bruce Alberts, Wei Yu, Guillermo Fernandez de la Garza, Jorge Allende, and many others). It has developed in nearly a hundred countries in the form of pilot projects of various amplitude, and has an important development in France, under the name of *La main à la pâte*.[21] Its roadmap is to provide support to teachers (primary, secondary and possibly high school) to help them teach science in an attractive way, involving active student participation in observation, experimentation, hypothesis making, argumentation, and reasoning. The scientific community is closely associated to the support and professional development of teachers, the production of relevant resources for the classroom, and the creation of national and international networks. The considerable development of these actions in the world has contributed to fuel wonder, curiosity, imagination, rationality and understanding of the processes on which science is built for over ten million schoolchildren. This development offers a sound basis for the emergence of climate change education. Nevertheless, additional elements will have to be included: economical and social issues; and ethical values.

4. A proposal to implement Climate Change Education worldwide

On December 12, 2017 a political *One Planet Summit* was called in Paris, exactly two years after the COP21. Focusing on financial issues, this Summit did not deal with education. Nevertheless, the InterAcademy Partnership for science (IAP) issued on this occasion a Statement approved by a majority of the 113 science Academies grouped under IAP. This detailed Statement, titled *Climate Change and Education*,[22] was prepared by a large group of experts, designated by these Academies. Some of its headlines messages are quoted as follows, and provide guidelines for future actions:

a. *Climate change education must consider the need to provide teachers, in developed as well as in developing countries, with up-to-date facts, new and innovative* *training processes, new resources for the classroom, and new tools to empower their students as 'agents of change'.*

b. *Inquiry-based science education (IBSE), developed over the last two decades, has demonstrated an effective way to teach science at primary and secondary school levels and also to inspire higher education worldwide. It provides a firm basis to develop urgently a specific, interdisciplinary climate change education programme.*
c. *Climate change and associated events will disproportionately impact the poorest three billion of the global population, whose schooling is far from adequate. Climate justice calls for supporting their schools and their teachers with specific initiatives.*
d. *International collaboration, through the involvement of the science community, will greatly enhance the mobilization of educational systems. As the Intergovernmental Panel on Climate Change (IPCC) is producing periodic 'Assessment Reports', accompanied by 'Summaries for Policy Makers', the scientific community should use the material from the IPCC reports to produce 'Resources & Tools for Teachers'.*

In the course of preparing this Statement, several remarkable projects, aiming at climate change education and teachers preparation, were quoted. Let mention here the efforts in Australian schools,[23],[24] in India, at Carleton College[25] in the United States, or in France with *La main à la pâte*[26] or *Le Train du Climat*,[27] while many experts from developing countries pointed out the urgent need of actions in education. There clearly exists a background on which to build the program outlined in *item d* of the Statement.

This *item d* calls for 'Resources and Tools for teachers' to be published in phase with the IPCC Reports and deserves particular attention. It is currently leading to an initiative, in continuity with the above-mentioned efforts (Section 1). This initiative emerges within the Fondation *La main à la pâte* in France, with the support of the Académie des sciences, the InterAcademy Partnership and the IPCC Group I, which is devoted to climate science. This initiative, named *Office of Climate Education*, owes special credit to Dr. Valérie Masson-Delmotte, climatologist and co-Chair of Group I, who fostered most of the initial ideas. During the years 2018-2022, the Office and its Network will publish resources for teachers worldwide, along with the planned reports of IPCC: Global Warming of 1.5°C (2018), Ocean and Cryosphere in a Changing Climate (2019), Climate Change and Land (2019), Sixth Assessment Report (2022).[28]

It is not the purpose of my contribution to present in detail the *Office*, being established in Paris, and its associated *Global Network for Climate Edu-*

cation.[29] Both are emerging in the frame of a French-German scientific and operational partnership (with the Siemens Stiftung); both would connect with the various networks which remarkably contributed to the Pontifical Academy of Sciences Workshop on *Children and Sustainable Development*, held in 2016.

We can enumerate here a list of attainable goals for students in almost any school in the world, if teachers are properly accompanied:
- Acquire basic scientific knowledge on climate science;
- Understand climate change in all its dimensions, both scientific and societal, at local and global levels;
- Develop their reasoning and critical thinking abilities;
- Develop their creativity, by discovering the prospects of innovation that can be explored by the struggle (mitigation and adaptation) necessitated by climate change, both in their daily lives and their future career choices;
- Perceive the profound changes in behaviour required, such as sobriety (especially in developed countries), promoting ethics and solidarity;
- Take concrete action at the scale of their school, family and community, to cope with climate change (mitigation and/or adaptation).

Conclusion

We have mentioned the contradiction in time scales between urgently required climate control and the slow pace of education changes. In his Encyclical Letter, Pope Francis says: *Although the contemplation of this reality in itself has already shown the need for a change of direction and other courses of action, now we shall try to outline the major paths of dialogue which can help us escape the spiral of self-destruction which currently engulfs us* (163). In this contribution, we have proposed to create a new and organised dialogue between the scientific community and the educators, especially the teachers, in developed as well as developing countries, in order for them to jointly contribute to an escape from self-destruction and to develop for the youth a positive vision of the future, where science would play its universal and creative role.

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References & Notes

1. Quotation from 'Atomic education urged by Einstein', *New York Times*, May 25, 1946, p. 13. The text refers to a telegram, published the previous day by the Emergency Committee of Atomic Scientists, chaired by Albert Einstein. Other sentences with similar meaning are often 'quoted', but their sources remain untraceable (https://en.wikiquote.org/wiki/Albert_Einstein).
2. https://ipcc.ch/report/ar5/
3. *Sustainable Humanity, Sustainable Nature, our Responsibility*. Dasgupta, P.S., Ramanathan, V., Sánchez Sorondo, M. (Eds.), Pontifical Academy of Sciences Extra Series 41, Libreria Editrice Vaticana, Vatican City, 2015.
4. Pope Francis. Encyclical Letter *Laudato Si'*. May 2015. http://w2.vatican.va/content/francesco/fr/encyclicals/documents/papa-francesco_20150524_enciclica-laudato-si.html
5. Sustainable Development Goals, United Nations, 2015. https://sustainabledevelopment.un.org/?menu=1300
6. *Education for people and planet: Creating sustainable development for all.* Global Education Monitoring Report 2016, UNESCO, Paris, 2016.
7. Adoption of the Paris Agreement, Framework Convention on Climate Change (UNFCCC), Dec. 2015. http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf
8. UN Framework Convention on Climate Change, 1994. http://unfccc.int/essential_background/convention/items/6036.php
9. *Children and Sustainable Development. Ecological Education in a Globalized World*. Battro, A., Léna, P., Sánchez Sorondo, M., Eds. Springer, 2016.
10. *Séminaire Education et Climat*. Académie des Sciences et Techniques Hassan II. Side Event COP22, Rabat, Nov 11, 2015.
11. *Développement durable, Changement climatique et Education*, Colloquium at the French Académie des sciences. Nov. 2016. http://www.academie-sciences.fr/fr/Colloques-conferences-et-debats/developpement-durable-changement-climatique-et-education.html
12. Laurent Fabius, *Conclusion of the Colloquium*. http://www.academie-sciences.fr/pdf/conf/colloque_031116/24_fabius.pdf
13. https://fr.wikipedia.org/wiki/Ignace_Philippe_Semmelweis
14. *Catastrophic Migrations in the XXIst Century*, Suarez-Orozco, M. & Sánchez Sorondo, M. (Eds.), University of California Press, 2018 (in press).
15. Pew Research Center, 2015. http://www.pewglobal.org/2015/11/05/global-concern-about-climate-change-broad-support-for-limiting-emissions/
16. *Climate change: a challenge for science education,* International School of Science Education, Erice (Sicily), D. Wilgenbus dir., 2017. https://sites.

google.com/a/fondation-lamap.org/climate-erice-2017/
See also the Conclusive Statement, *ibid.*
17. Corner, A. *et al.*, 'How do young people engage with climate change. The role of knowledge, values, message framing and trusted communicators'. *WIREs Clim. Change*, 6: 523-534. doi:10.1002/wcc.353
18. Ramanathan, V., Hahn, H., Matlock, T., 'Educating Children to Bend the Curve: For a Stable Climate, Sustainable Nature and Sustainable Humanity', in *Children and Sustainable Development,* op. cit.
19. Léna, P. 'Faut-il faire simple à l'école quand le monde est si complexe ?', *Résonances. Mensuel de l'Ecole Valaisane*, n°2, Oct. 2014.
20. Edgar Morin, *Le Défi de la complexité*, Casa Editrice Le Lettere, Firenze, 2011, p. 78 sqq.
21. *Globalisation and Education,* Sánchez Sorondo, M., Malinvaud, E., Léna, P. (Eds.) A Joint PAS & PASS Workshop, 16-17 Nov. 2005, PAS Extra Series 28, Walter de Gruyter, Berlin-New York, 2007. (See also Ref. 26).
22. *A Statement on Climate Change and Education*, from the Academies members of IAP for Science, Dec. 2017. http://www.interacademies.org/Statements.aspx
23. *Science by Doing, A Unit on Big Systems*, https://www.sciencebydoing.edu.au/
24. *The science of Climate Change. Questions and Answers*, Australian Academy of Sciences, 2015. https://www.science.org.au/learning/general-audience/science-booklets-0/science-climate-change
25. Manduca, C., Science Education Resource Center, Carleton College (USA), serc.carleton.edu
26. Fondation *La main à la pâte.* www.fondation-lamap.org
27. *Le Train du Climat*, trainduclimat.fr, 2017.
28. Intergovernmental Panel on Climate Change, https://ipcc.ch/
29. Office of Climate Education (OCE). http://www.fondation-lamap.org/oce-creation-en

SPECIAL SESSION

Cosmology on the Occasion of the 50th Anniversary of Msgr. Georges Lemaître's Death

The Future of Space Exploration and Technology

Martin J. Rees

I'll start with a flashback to Isaac Newton. He must have thought about space travel. Indeed, there is a famous picture, in the English edition of his *Principia*, which depicts the trajectory of cannon balls being fired from a mountaintop. If they are fired fast enough, their paths curve downward no more sharply than the Earth's surface curves away underneath them: the cannon-balls go into orbit. This is still the neatest way to teach the concept of orbital flight.

Newton could calculate that, for a cannon-ball to achieve an orbital trajectory, its speed must be 25000 km/hour. But that speed wasn't achieved until 1957 with the launch of Sputnik 1. Only twelve further years elapsed between the historic 'one small step for a man' on the lunar surface in 1969. I never look at the Moon without being reminded of Neil Armstrong and Buzz Aldrin. In retrospect, when we realize the primitive computing support available at that time, and the untested equipment, this exploit seems even more heroic and historic – especially as the Apollo programme remains, a half-century later, as the high point of human ventures into space. This programme was conceived as a 'space race' against the Russians. Once that race was won, there was no motive for continuing massive expenditure. In the 1960s NASA absorbed more than 4% of the US federal budget. The figure today is 0.6%. Had the higher momentum been maintained, there would surely be footprints on Mars by now: that's what our generation expected.

It's nearly 45 years since Apollo 17, the last lunar mission, returned to Earth. Today's young people know the Americans landed men on the Moon. They know the Egyptians built pyramids. But these both seem ancient history, motivated by almost equally bizarre national goals.

Hundreds more have ventured into space in the ensuing decades – but, anticlimactically, they have done no more than circle the Earth in a space station. The International Space Station (ISS) was probably the most expensive artifact ever constructed. Its cost, plus that of the Shuttles whose main purpose was to service it (though they have now been decommissioned), ran well into twelve figures. The scientific and technical payoff hasn't been negligible, but it's been immensely less cost-effective than unmanned missions. Nor are these voyages inspiring in the way that the heroic pioneering Russian and US space exploits undoubtedly were. The ISS only makes news when something goes wrong: when the plumbing or electronics fail – or when astronauts perform 'stunts', such as the Canadian Chris Hadfield's guitar-playing and singing.

Despite the languishing of manned spaceflight, space technology has of course burgeoned: we depend routinely on orbiting satellites for communication, sat-nav, environmental monitoring, surveillance, and weather forecasting. And many nations – not just the superpowers – undertake space projects. Much of this work involves spacecraft which, though unmanned, are expensive and elaborate. (Indeed the GPS and Galileo systems on which sat-nav depends need to be so precise that the gravitational corrections in clock rates due to general relativity must be taken into account: this is the first technological application of Einstein's general relativity.)

But dramatic advances in miniaturisation and computing power have enabled the manufacture of cheaper standardized spacecraft. For instance, the San Francisco-based company 'Planet' has launched 70 shoebox-sized spacecraft as payload on a single Indian rocket. Their collective purpose is to give global coverage of the Earth's surface, albeit at not-specially-sharp resolution. The mantra (with only slight exaggeration) is to observe every tree in the world every day. The system is optimized to observe changing land-use, construction projects, and so forth. There is a market for 'cubesats' only 10 centimetres in size. And even smaller wafer-thin satellites can now be deployed, basically using the same amazing technology that has emerged from the high investment in smartphones.

Space telescopes have been hugely important for astronomy. Orbiting far above the blurring and absorptive effects of Earth's atmosphere, they have beamed back data from the remotest parts of the cosmos, in wavebands such as infrared, UV, x-rays and gamma rays which can't be observed from the ground. They have revealed new cosmic phenomena, and probed with high precision the 'afterglow of creation '– the microwave radiation pervading all space whose properties hold clues to the very beginning, when the entire observable cosmos was squeezed to microscopic size.

Of more immediate public appeal – because more readily comprehensible – are the data from spacecraft that have journeyed to all the planets of our Solar System. NASA's 'New Horizons' probe beamed back amazing pictures from Pluto, 10,000 times further away than the Moon. And ESA's Rosetta has landed a robot on a comet. These spacecraft took five years to design and build, and then 10 years journeying to their remote targets; so they embody old-fashioned technology. And Cassini is even more of an antique: more than 20 years elapsed between its launch and its final plunge into Saturn in late 2017.

We're aware how mobile phones have changed in the last 15-20 years – so imagine how much more sophisticated today's follow-ups to these missions could be.

During this century, the entire Solar System – planets, moons and asteroids – will be explored and mapped by flotillas of tiny robotic craft, interacting with each other like a flock of birds. Giant robotic fabricators will be able to construct, in space, huge solar-energy collectors and other artifacts. The Hubble Telescope's successors, with huge gossamer-thin mirrors assembled under zero gravity, will further expand our vision of stars, galaxies and the wider cosmos. The next step would be space mining and fabrication. (And fabrication in space will be a better use of materials mined from asteroids than bringing them back to Earth).

It's robots, and not humans, that will build giant structures in space. And sophisticated robots will explore the outer planets: they will have to utilize the techniques of deep learning and AI to make autonomous decisions – the travel time for a radio signal to the outer planets is measured in hours or even days, so there's no possibility of direct control from Earth. These robots won't be humanoid in size and shape. Humans are adapted to the Earth's environment. Something more spider-like would be better suited to the weaker gravity of Pluto or the asteroids

But will these endeavours offer a role for humans? There's no denying that NASA's 'Curiosity', a vehicle the size of a small car that has since 2011 been trundling across Martian craters, may miss startling discoveries that no human geologist could overlook. But machine learning is advancing fast, as is sensor technology; whereas the cost gap between manned and unmanned missions remains huge. The practical need for manned spaceflight gets ever weaker with each advance in robots and miniaturization.

Nonetheless I hope some people now living will walk on Mars – as an adventure, and as a step towards the stars. But NASA or ESA will confront political obstacles in achieving this goal within a feasible budget.

NASA's manned programme, ever since Apollo, has been impeded by public and political pressure into being too risk-averse. The Space Shuttle failed twice in more than 130 launches. Astronauts or test pilots would willingly accept this risk level, but the Shuttle had, unwisely, been promoted as a safe vehicle for civilians. So each failure caused a national trauma and was followed by a hiatus while costly efforts were made (with very limited effect) to reduce the risk still further.

China has the resources, the dirigiste government, and maybe the willingness to undertake an Apollo-style programme. If it wanted to assert its super-power status by a 'space spectacular' and to proclaim parity, China would need to leapfrog, rather than just re-run, what the US had achieved 50 years earlier. A permanently manned lunar base would be one option. But a clearer-cut 'great leap forward' would involve footprints on Mars, not just on the Moon.

But, leaving aside the Chinese, the future of manned spaceflight lies with privately-funded adventurers, prepared to participate in a cut-price programme far riskier than NASA or ESA would countenance. That's why these organizations should share expertise and collaborate with outfits like Space X, led by Elon Musk (who also builds Tesla electric cars) or the rival effort, Blue Origin, bankrolled by Jeff Bezos, founder of Amazon. Their spacecraft have docked with the Space Station and hope soon to offer orbital flights to paying customers. These companies – bringing a Silicon Valley culture into a domain long-dominated by NASA and a few aerospace conglomerates – have shown it's possible to recover and reuse the launch-rocket's first stage – presaging real cost-saving. (They have advanced the techniques of rocketry far faster than NASA or ESA has done – these governmental organizations will in future have a more limited role more akin to an airport than to an airline).

Indeed, it would be best to let inspirationally-led private companies 'front' all the manned missions. These private ventures can tolerate higher risks than a western government could impose on publicly-funded civilians; they can thereby cut costs compared to NASA (or ESA). There would, nonetheless, be many volunteers – accepting high risks and perhaps even 'one-way tickets' – driven by the same motives as early explorers, mountaineers, and the like. (The phrase 'space tourism' should be avoided. It lulls people into believing that such ventures are routine and low-risk. And if that's the perception, the inevitable accidents will be as traumatic as those of the Space Shuttle were. Instead, these cut-price ventures must be 'sold' as dangerous sports, or intrepid exploration).

But there could be technical breakthroughs in the longer-term. The most crucial impediment to space flight, even in Earth's orbit and still more for those venturing further, stems from the intrinsic inefficiency of chemical fuel, and the consequent requirement to carry a weight of fuel far exceeding that of the payload. (It's interesting to note, incidentally that this is a generic constrain, based on fundamental chemistry, on any organic intelligence that had evolved on another planet. If a planet's gravity is strong enough to retain an atmosphere, at a temperature where water doesn't freeze and metabolic reactions aren't too slow, the energy required to lift a molecule from it will require more than one molecule of chemical fuel).

So long as we remain dependent on chemical fuels, interplanetary travel will remain a challenge. A space elevator would help. But nuclear power could be transformative. By allowing much higher in-course speeds, it would drastically cut the transit times to Mars or the asteroids (reducing not only astronauts' boredom, but their exposure to damaging radiation). And lasers on the ground can accelerate small spaceprobes to high speeds.

By 2100 thrill-seekers in the mould of (say) Felix Baumgartner, who broke the sound barrier in free fall from a high-altitude balloon, may have established 'bases' independent from the Earth – on Mars, or maybe on asteroids. Elon Musk of Space-X (born in 1971) says he wants to die on Mars – but not on impact.

But don't ever expect mass emigration from Earth. And here I disagree strongly with Elon Musk, and with my colleague Stephen Hawking, who promote rapid build-up of large-scale Martian communities. I think it's a dangerous delusion to claim that space offers an escape from Earth's problems. We've got to solve them here. Coping with climate change is a doddle compared to terraforming Mars. Nowhere in our Solar system offers an environment even as clement as the Antarctic or the top of Everest. There's no 'Planet B' for ordinary risk-averse people.

But we (and our progeny here on Earth) should cheer on the brave space adventurers. This is because they will have a pivotal role determining what happens in the 22nd century and beyond – and even spearheading the transition to a post human era.

A century or two from now, there may be small groups of pioneers living independent from the Earth – on Mars or on asteroids. Precisely because space is an inherently hostile environment for humans, these pioneers will have far more incentive than us on Earth to re-design themselves. They'll harness the super-powerful genetic and cyborg technology that will be developed in coming decades. These techniques will be heavily regulated on Earth, but Martian colonists will be far beyond the clutches of the regulators.

Whatever ethical constraints we impose here on the ground, we should surely wish these adventurers good luck in genetically modifying their progeny to adapt to alien environments. This might be the first step towards divergence into a new species: the beginning of the post-human era. And genetic modification would be supplemented by cyborg technology – indeed there may be a transition to fully inorganic intelligences.

So it's these thrill-seeking spacefarers, not those of us comfortably adapted to life on Earth, who will spearhead the post-human era.

Organic humans like us need a planetary surface environment – but if posthumans make the transition to fully inorganic intelligences, they won't need an atmosphere. And then may prefer zero-g, especially for constructing massive artifacts. So it's in deep space – not on Earth, not even on Mars – that non-biological 'brains' may develop powers than humans can't even imagine.

Few doubt that machines will gradually surpass more and more of our distinctively human capabilities – or enhance them via cyborg technology. Disagreements are basically about the timescale – the rate of travel, not the direction of travel. The cautious amongst us envisage timescales of centuries rather than decades for these transformations. Be that as it may, the timescales for technological advance are but an instant compared to the timescales of the Darwinian selection that led to humanity's emergence – and (more relevantly) they are less than a millionth of the vast expanses of cosmic time lying ahead.

So in a cosmic perspective, the present era, dominated by humanity and its artifacts represents a thin sliver between the four billion years of pre-human Darwinian evolution, and the billions of future years of evolution via technological 'intelligent design' – here on Earth and far beyond.

Exploiting Solar System Resources: Opportunities and Issues

Br. Guy Consolmagno SJ

Asteroid Research

Asteroids are small rocky bodies (generally less than 100 km diameter, most of them smaller than 10 km) orbiting the Sun often in orbits between Mars and Jupiter, a region known as the Asteroid Belt. They are considered the fragments of the original material which made up the solid parts of the planets in our solar system.

There exist three motivations for wishing to understand the structure of asteroids. The main motivation behind our work at the Vatican Observatory is to understand the formation of the planets, 4.6 billion years ago. For example, we have reason to believe that meteorites, which have radioactive closure ages of about 4.6 billion years, represent samples of those asteroids and thus their study can give us clues to the evolutionary history of the solar system itself.

There is another motivation for understanding the physical nature of the asteroids today, however. We now recognize that some asteroids do on occasion become perturbed into Earth crossing orbits, and some small fraction of those could potentially represent a threat to Earth's inhabitants. These events are not limited to the sorts of impact events like that which is thought to have triggered the mass extinctions of the K-T event 65 million years ago. Our best estimates now suggest that such enormous impacts are a once in a hundred million years event. But smaller, more common events can also have important effects on terrestrial life.

When the meteorite that formed Meteor Crater in Arizona hit, only 50,000 years ago, its impact was equivalent to a 10 megaton nuclear explosive. The force of the winds produced by the shock would have produced hurricane-level devastation in an area up to 40 of kilometers away from the impact site.

An impact like that is still relatively rare, but even smaller impacts could still have serious local effects. On 15 February 2013, the 30 m diameter asteroid 2012 DA14 (30 m) passed closer to Earth than the orbital altitude of geosynchonous satellites. On the same day, a completely unrelated 18 m fragment hit the Earth's atmosphere and exploded over the Russian city of Chelyabinsk; more than one thousand people were treated for injuries, mostly from flying glass as the sonic boom of the impactor shattered windows across this city of more than 1,000,000 inhabitants. It is estimated that objects similar to the Chelyabinsk impactor (fragments of which have been recovered, and shown to be made of ordinary chondrite material) probably hit the Earth at least once a decade.

There is a third motivation for studying asteroid composition and structure, however, which ties directly to the theme of Science and Sustainability. Within the next few decades these asteroids may well become new sources of natural resources. In fact, several asteroid mining companies are already set up and running, and NASA is actively working on the basic engineering of Space Mining. The exploitation of these resources presents both opportunities and cautions of which society should be aware.

The Meteorite-Asteroid Connection

One unique aspect of asteroid science is the recognition that we have in fact thousands of physical samples of the asteroids in our terrestrial meteorite collections, available for chemical and physical studies. From such measurements we can actually make specific claims about the composition and physical structure of asteroids.

There are many different lines of evidence supporting the meteorite-asteroid connection.

Some two dozen fireballs have been imaged from multiple locations with enough detail to allow one to trace their orbits, which have dropped meteorites onto the surface of the Earth that have been collected and shown to be typical meteorites. In every case, the observed orbits of the fireballs trace back to the asteroid belt.

Another strong line of evidence is to compare the observed spectra of the asteroids, especially in the near infrared where certain minerals produce diagnostic broad band features. These features in many asteroids match the features in both wavelength and shape of features measured for ordinary chondrite meteorites in the lab.

The most telling evidence, of course, comes from returned samples. The Japanese Hayabusa mission to the small asteroid Itokawa brought back particles of dust whose chemical compositions exactly matches samples of the a particular ordinary chondrite subgroup, the LL group. Other sample return missions, including the NASA OSIRIS-REx mission and the JAXA Hayabusa II missions, are already launched and en route to their respective asteroid targets.

Just as the most common stony meteorites can be classified generally into two main groups, ordinary and carbonaceous, the most common asteroids likewise can be sorted into two main groups, "S" and "C", based on their colors and brightness. Where Hayabusa visited an S asteroid, the two missions currently en route are both targeted to the as-yet-unsampled C type asteroids. By the early 2020s we will have solid data to connect these different asteroid spectra types with the different classes of meteorites (there do exist a relatively rare class of E-type asteroids which are though to be the source of enstatite chondrites, but this connection has yet to be confirmed).

Meteoritics at the Specola Vaticana

The primary research in meteoritics at the Vatican Observatory is measuring the physical properties of meteorites… their density, porosity, magnetic properties, and thermal properties. It is work that I began in collaboration with Prof. Daniel Britt at the University of Central Florida back in 1996, and it is being carried forward now at the Observatory, with Dr. Britt and other collaborators as part of a NASA funded Center for Lunar and Asteroid Surface Studies, with the active participation of our current curator of meteorites, Br. Robert Macke SJ. Several dozen refereed papers and research presentations have resulted from this work, which have been summarized in two review papers in the journal *Chemie der Erde.*[1]

The Vatican meteorite collection is ideal for such survey work. The bulk of the collection consists of more than a thousand samples representing nearly every meteorite type from the comprehensive collection of the Marquis de Mauroy, donated to the Vatican by his widow in 1935.

Meteorites come in many different chemical and physical varieties, which has provided both challenges and opportunities for our work. However, for the purposes of the discussion in this paper, we can summarize the general groupings in this way.

About 85% of the meteorites that are seen to fall to Earth belong to a class called *Ordinary Chondrites*. The relative abundances of the chemical elements in these rocks closely parallels that seen in the atmosphere of the Sun itself, and they are thought to represent material similar to what made up the bulk Earth and other terrestrial planets. These elements are present as a mixtures of basic rock-forming elements, such as olivine, pyroxene, and

[1] Consolmagno *et al.*, *Chemie der Erde* 68, 1-29 (2008); Flynn *et al.*, *Chemie der Erde*, in press.

plagioclase, which are found in small (less than a millimeter) beads called "chondrules", held in a matrix of well-compressed fine grains. The matrix generally has the same composition as the chondrules, but in addition one finds distributed through the matrix many sub-millimeter flakes of iron-nickel metal, which contain as well the other metallic elements such as platinum and gold also present in the same relative abundances as seen in the Sun.

The next most common meteorite class are meteorites which are far more oxidized than the ordinary chondrites and with other distinctive chemical trends. They are known as *Carbonaceous Chondrites*. They make up about 8% of observed meteorite falls.

The name "carbonaceous" for this group can be misleading. While there are some meteorites within this group that contain up to 20% bound water and 5% or more carbon-bearing organic material, giving the group its name "carbonaceous", there are many other meteorites now classified with these meteorites but which have essentially no carbon or water. More challenging, both the volatile-rich and volatile-poor members of this class tend to be very dark, which tends to suppress those spectral features in the visible or near infrared that would help distinguish one type from another either. Thus it is not easy to determine by remote sensing whether a given black rock is a volatile rich CI meteorite, a volatile poor CV meteorite... or an ordinary chondrite that has been turned black by shock.

The final chondrite class, the *Enstatite Chondrites*, make up 5% of observed falls. They are chemically the opposite of the carbonaceous meteorites, being chemically highly reduced but 20% to 25% by mass iron-nickel metal. They also contain interesting but at times exotic minerals rich in chromium, manganese, and titanium.

The other 9% of the meteorites seen to fall to Earth consist of a wide range of scientifically fascinating materials, whose study can provide great clues to the processes that occurred when our solar system was forming. For the purposes of the discussion below, however, it is sufficient to note that they are all quite rare. In particular, though the meteorites seen in museums often tend to be large pieces of metal, know collectively as *Irons*, such meteorites are actually rarely seen to fall. Their dominance in our collections is the result purely of the fact that they are very easy to identify even by the casual observer when found among terrestrial rocks; and, unlike the ordinary chondrites, they can survive weathering in the water- and oxygen-rich atmosphere of Earth (typically, an ordinary chondrite is rusted into dust within a hundred years of sitting on the Earth's surface, except in dry places like the Sahara or Antarctica. By contrast, iron meteorites can survive on Earth for thousands of years).

This classification of meteorites by chemical type is the fruit of a century's worth of painstaking work in collections around the world. The bulk of the laboratory analysis done on meteorites today carries this work forward by using a variety of high-tech analytical devices to determine the precise compositions and isotopic characteristics of ever-smaller samples, in order to put ever tighter constraints on the chemical evolution of these samples.

However, as such work (strongly fueled by the need to analyze lunar samples from the Apollo era) was progressing in the latter half of the 20th century, the measurements of the physical properties of meteorites had not kept pace with our growing knowledge of meteorite chemistry. With that in mind, starting about 25 years ago, certain laboratories in Finland, Canada, Japan, and our group at the Vatican began the systematic measurement of meteorite physical properties: density, porosity, magnetic susceptibility, heat capacity, thermal and electrical conductivity, and strength under compression and extension. Knowing these properties is essential for understanding the physical evolution of the planets, and the planetoids from which they were formed. But, as we will see, it also has given us a tool for a completely different sort of endeavor.

The first stage of our work at the Vatican in measuring physical properties has been to determine the average bulk and grain densities of meteorite groups. These measurements, now essentially complete, are based on a survey of more than a thousand meteorites not only in our collection but samples obtained by taking our measurement equipment to collections around the world.

We found that bulk densities (where the volume of internal voids is included in the calculation of density) of most ordinary chondrite meteorites range from 2.8 to 3.6 g/cm^3. The bulk of these samples have relatively low porosity, under 10%, which generally can be accounted for by the shock-induced microcracks imposed on the matrix of the sample long after its formation. By contrast, many carbonaceous chondrite meteorites turn out to be more porous than the ordinary chondrites, with the result that they have lower bulk densities. In particular, those carbonaceous meteorite types that are rich in organic materials and hydrated minerals (with OH or actual water present), the CI and CM groups, have much lower densities. For the most water rich meteorites, the bulk density is in the range of 2 to 2.5 g/cm^3; the lowest bulk densities, for the two most water rich meteorites, are 1.6 g/cm^3 reflecting not only the large amount of OH present but also their intrinsic high (up to 30%) porosities.

Asteroid Physical Properties

Whereas spectra only characterizes the surface layers of an asteroid, bulk physical properties such as density allow us to examine the content of the entire asteroid. Given this connection between meteorites and asteroids, it thus is interesting to compare the physical properties of the meteorites that we have measured with those properties of the asteroids themselves. In particular, the comparison between the densities of the meteorites we have measured with the densities of the asteroids where they are thought to be derived is of particular interest, and provides several important constraints on our understanding of how we might exploit those asteroids for their natural resources. Over the past twenty years, asteroid densities have been derived by a number of different techniques.

The average dimensions of an asteroid can be determined from ground-based observations in a number of ways. The observed brightness of an asteroid depends on three factors. Given that one is measuring the intensity of sunlight reflected from the asteroid, the amount of light we observe is in part determined by the distances of the asteroid from the Sun (and from us). The location of the asteroid is easily determined by knowing the rate of its orbit, using Kepler's Laws. A second factor is the intrinsic reflectivity of the material on the asteroid's surface, its *albedo.* For a given solar distance, a darker surface will absorb more sunlight than a brighter surface; thus, if its temperature can be determined by the observing in the infrared the shape and position of its black body radiation, one can then deduce its average albedo. Finally, the amount of visible light reflected from an asteroid surface depends on both its albedo and its size; and so, given the albedo determined from infrared observations, the size of the asteroid can then be calculated. Such measurements are nowadays typically quoted to a value of plus or minus ten percent.

Size is one essential factor in determining an asteroid's density; mass is the other essential factor. It is in fact a distinct challenge to be able to determine the mass of an asteroid; this can be done only by determining how the asteroid affects the orbits of some other object. With the advent of spacecraft missions into the asteroid belt, we can use the measured deflection of any spacecraft that passes close to an asteroid (or even better, by measuring the orbit of such a spacecraft about that asteroid) to derive very precise mass measurements. In addition, however, over the past twenty years improvements in ground based telescopes using adaptive optics have allow us to detect natural moonlets in orbit around many dozens of asteroids; their orbits likewise allow one to determine the masses of the asteroids.

Only a few dozen asteroids in total have had both mass and size measured, to date, but the results of these measurements are quite startling: the observed asteroid densities range from 1.3 g/cm^3 to 2.8 g/cm^3 with the C type asteroids systematically less dense than the S types. In other words, the densities of asteroids appear in general to range from 25% to 50% less dense than the meteoritic material from which they are made. The inference is that asteroids today are not solid bodies, but rather loose piles of rubble.

This conclusion leads to the realization that the asteroids must have had a very complex evolutionary history. At the very least, the dust in the original solar nebula from which all solid bodies are derived must first have experienced an environment where it could be compacted into solid rocky material with low porosity, as seen today in most meteorites, while being accreted into large coherent bodies that then were catastrophically disrupted and re-accreted. How many times has this catastrophic disruption taken place? What is the relative time scale of the lithification versus accretion? What limits can we place on the times when each of these events occurred? The answers to all these questions will give us some fundamental markers as to what occurred at the same time that the larger planets, including Earth, were forming.

Asteroids, Resources, and Issues in Sustainability

About half a million asteroids have already been discovered, most of them orbiting in the region of space between Mars and Jupiter, and most of them smaller than about ten kilometers in radius. From studying the distribution of asteroid sizes it is possible to estimate the overall population of asteroids, including those which because of their small size have not yet been discovered. (Our surveys of the main asteroid belt are probably complete only down to a diameter of 10 km). It is clear that the smaller bodies are the more numerous bodies, and that the largest number of asteroids are to be found in size ranges too small to be easily detected yet from Earth.

This conclusion is especially important when we examine the small subset of these asteroids which are known to follow eccentric orbits that carry them in from the asteroid belt to cross the orbit of Earth. Several thousand such objects are already known, and there is an active research program whose goal is to be able to track the orbits of at least 90% of the computed population. Because they come closer to Earth, many such Near Earth Objects (NEOs) as small as a few tens of meters have been observed; using the same sort of size distribution statistics one can estimate that many thousands of such objects, similar to that which exploded over Chelyabinsk, remain to be found. Already we are finding small NEOs arriving as close to Earth as the orbit of the Moon at a rate of about one a month.

Obviously, the smaller the object the more numerous they are; but the harder they are to discover, and the more difficult it is to be able to predict when one of that size might arrive close to Earth. In planning to find an asteroid that might be exploited, a size of about 1 km diameter seems like a good first guess.

A simple, very naive calculation may help set the stage for us to appreciate the scale of the resources being talked about. First, for ease of calculation, let us simply assume that such an asteroid is spherical; thus the volume of a 0.5 km radius asteroid is about 0.5×10^9 cubic meters. If it is a typical S type asteroid, made of ordinary chondritic material but battered into a rubble pile that is 40% empty space, we would expect it to have a bulk density of about 2×10^3 kg/m^3 and thus a total mass of 10^{12} kilograms.

What material in an ordinary chondrite might be considered worth exploiting? Recall that about ten percent of the mass of such a meteorite is metal, primarily iron and nickel but also containing significant traces of more valuable metals such as gold, platinum, copper, silver, or zinc. Continuing our naive calculation, we can assume that our typical asteroid has these metals in the abundances found in meteorites; we then look up what these metals sell for typically on the open market today; and finally add up the various monetary values to arrive at the worth of the entire asteroid.

The result looks startling. The iron alone constitutes 15 million metric tons of material; given a value of a few hundred dollars per ton, one can easily see that it is worth on the order of about ten billion dollars.

In fact, at current values for rare metals, the iron makes up about half the value of the metals in total, since the more valuable metals are of course much rarer. Still, one might expect that disassembling a 1-kilometer asteroid made of ordinary chondritic material would yield metals worth on the order of $20 billion.

A casual perusal of this calculation shows that it is indeed naive. Obviously it does not reflect at all how the markets for these raw materials would be affected by the arrival of such a new and plentiful source. Nor it does not take into account how expensive it would be to actually rendezvous with such an asteroid, disassemble it, and bring the materials back to Earth. The latter is more difficult than it might seem at first glance; the relentless laws of celestial mechanics tell us that an NEO which comes into a close pass to Earth, and thus easy to reach at that time, will cross Earth's orbit again many, many times before actually encountering Earth again at the same time. It may take tens to hundreds of years before the asteroid returns close enough to Earth to allow for the easy return to us of whatever material has been dug out and packaged for our use.

Going after a smaller NEO would undoubtedly reduce the cost of exploitation, and allow it to be exploited while it is still close to Earth. With the same simple assumptions, what would be the value in a 15-meter ordinary chondrite, similar to the meteoroid that exploded over Chelyabinsk? Remember that an object this small would probably not be a rubble pile (rather, something that small is probably one of the bits of the rubble). Thus it would have a higher density, increasing the amount of valuable metals to be found within it. Even with that advantage, though, we can calculate that it would likely have a mineral value of only about $150,000… hardly worth the investment of millions of dollars for a spacecraft to go and capture it. Indeed, it would be worth more if one were to sell bits of it to meteorite collectors at the going prices for common meteorites.

Of all the questionable assumptions in the calculation above, however, the one that is most certainly not correct at least at the present time is that the most valuable use of such NEO resources would be resources for terrestrial consumption. In fact, the most prized resources in the short run may not be metals to be sent back to Earth, but water and oxygen that could be used to make rocket fuel in space, and thus support the exploration or indeed human life in space itself. That being the case, C type asteroids that are made of water-rich carbonaceous chondrite material are particularly prized for their OH content (recall that such asteroids are the targets of two ongoing space missions).

This is the motivation currently driving the nascent space resources community. Among the companies currently set up for this work include Deep Space Industries, Kepler Energies and Space Engineering, and Planetary Resources; a look at their web pages goes into great detail about what they hope to do, and how they hope to do it.

The US National Aeronautics and Space Administration (NASA) is actively working on the basic engineering of space mining a program; their web site discusses topics such as how to attach the equipment to the asteroid surface under very low gravity, how to excavate the regolith, and possible ways of extracting metals.

Luxembourg and other small countries, including the United Arab Emirates and the Isle of Man, are setting themselves up as hosts for entities looking for a favorable place to incorporate themselves. For example, Luxembourg has established a "Space Cluster" to promote space business and in September 2016 a meeting titled "Asteroid Science Intersections with In-Space Mine Engineering" was held at the University of Luxembourg, attracting both space scientists and planetary astronomers.

Social Implications

The short-term use of space resources will be to make it easier to travel in space. But the long-term purpose of such space travel is, ultimately, the exploitation of space for human purposes. These activities can range from scientific explorations, to tourism, to health care in low gravity, to manufacturing that makes use of non-stop solar energy... and nearby, easily exploitable space resources.

Our near Earth environment, with a steady supply of NEOs, would provide an essentially unlimited supply of resources while solar power in space, not limited to the vagaries of weather or a day/night cycle, would provide the energy to manufacture these resources into useful products. Mining and manufacturing on Earth puts an enormous stress on its environment; moving mining and manufacturing off-planet would preserve the natural setting and beauty of our irreplaceable planet. All of these benefits make the eventual exploitation of space resources very attractive and in some ways necessary to be able to sustain our lives at a level of industrial sophistication that, at present, comes with a terrible environmental cost.

Note that both resources of space would be available to anyone who can get to them. Space is uninhabited, which means that such resources are not under the control of whoever happens to be living where they are found. But for this very reason, space resources will inevitably wind up exclusively in the hands of space-faring multi-nationals. Competition for the most easily exploited NEOs will require new ways of deciding what constitutes legitimate claims, and new ways of arbitrating such claims (similar issues exist already in the ownership of meteorites, where every nation has a different set of laws and standards). The best precedent for how to proceed is probably the already existing law of the sea.

If space resources replace resources mined on Earth, what will be the effect on the economies of those nations, often among the poorest, who rely on raw material exports to support their economies? If resources are obtained in space, undoubtedly most of the actual labor will be done by robots, pre-programmed and monitored remotely. This means that there would be little opportunity for employing the unskilled labor. What happens to those laborers, who are often among the poorest members of our society?

In his Encyclical *Laudato Si'*, Pope Francis has drawn an important light on the social and moral issues that accompany technological change, even change that on the whole has great promise to improve human life in the long run. Eliminating the jobs connected with extracting resources on Earth, jobs usually associated with areas of significant poverty and lack of opportunities, will undo the social structures that give those communities a cultural identity and sense of meaning of life. What will happen to them? Where will they go, and how will that affect the culture and economies of the places that receive them?

What can we think to do, now, to prepare for a future where these disruptions are likely to take place?

Conclusions

The research into meteorite physical properties at the Vatican Observatory was begun with a simple goal, to help better characterize these solar system materials and perhaps provide data useful to others who wish to understand the origin and evolution of asteroids. What has happened, however, is that our data have turned out to have a much wider utility than we could have imagined. In particular, they play a central role in characterizing asteroids that are potential targets for resource exploitation.

The immediate use for asteroid resources almost certainly will be to extract water and oxygen, whose utility is obvious not only for sustaining life in space but more immediately as a resource to produce rocket fuels to allow for more extensive exploration… fuel that otherwise would have to be lifted out of Earth gravity at enormous expense and inefficiency. It is not likely that any particular social disruption would come from these uses of space resources. But it must be acknowledged that the long-term result of making it easier to live and travel in space, will be the eventual exploitation of resources like those described here. What eventually will be the most disrupting action of our activities in space we cannot yet judge, any more than we could guess what our meteorite data would lead to.

Finally, to echo *Laudato Si'*, we must correct the present disparity between excessive technological investment in consumption and insufficient investment in the human family. Our goal must be to prioritize stability and avoid unnecessary disruption in the social fabric that inevitably accompanies technological change (and indeed would occur if we failed to use technology to respond to the changing needs of society). The criterion for how we judge our actions, ultimately, is love. Love, in our political, economic, and cultural spheres, must become the highest norm of our actions.

The Origin of the Universe[1]

Stephen W. Hawking

Can you hear me.

Hubble's discovery of the expansion of the universe, was one of the most important intellectual discoveries of the 20th century, or of any century. It transformed the debate about whether the universe had a beginning. If one traces the motion of the galaxies back in time, they would all have been on top of each other about 14 billion years ago. Georges Lemaitre was the first to propose a model in which the universe had such an infinitely dense beginning. So he, not George Gamow, is the father of the big bang.

Observational evidence, to confirm the idea that the universe was initially in a very dense state, came in October 1965, with the discovery of a faint background of microwaves throughout space. The only plausible explanation for the existence of this background of microwaves, is that it is radiation left over from an early time, when the universe was very hot and dense. As the universe expanded, the radiation cooled, until it is just the faint remnant we can detect today.

In order to understand the origin of the universe, we need to combine the general theory of relativity, with quantum theory. The best way of doing so, seems to be to use Feinman's idea of a sum over histories. Richard Feinman proposed that in quantum theory, a system gets from a state A, to a state B, by every possible path or history. In Feinman's picture, the probability for a state of the universe at the present time, is given by adding up the amplitudes for all the histories that end with that state. But how did the histories start.

It was at a conference in the Vatican, in 1981, that I first put forward the suggestion, that maybe time and space together, formed a surface that was finite in size, but did not have any boundary or edge. Together with James Hartle from the University of California, I worked out what physical conditions the early universe must have, if space time had no boundary in the past.

Note that there may be incorrect spellings, punctuation and/or grammar in this document. This is to allow correct pronunciation and timing by a speech synthesiser.

Our model became known as the no boundary proposal. It says that when we go back towards the beginning of our universe, space and time become fuzzy, and cap off, somewhat like the South Pole on the surface of the Earth. Asking what came before the Big Bang, is meaningless, according to the no boundary proposal, because there is no notion of time available to refer to. It would be like asking what lies South of the South Pole.

The State of Understanding of the Nature and Evolution of the Observable Universe

James Peebles

I offer in the first section an outline of major steps to the present standard and accepted theory of the large-scale nature and evolution of our universe. I comment on some open issues in Section 2.

1. Steps to our present understanding

The exploration of our physical world may be classified in a hierarchy of size scales. Some scientists examine the organization of molecules of atoms in biological systems, in all the complexities of their interactions. Others examine the atoms, a simpler task because there is a limited number of different atoms with appreciable lifetimes. And low atomic number atoms are simple enough to allow precision tests of the quantum theory of their structures. Others examine the behavior of the nuclei of atoms, and others the substructures of the protons and neutrons in atomic nuclei. On larger scales there is the rich study of the complexity of what is happening on our planet Earth. The wonderful varieties of physical situations on other planets and moons in our Solar System allow quite different things to be studied. At this meeting Lisa Kaltenegger discussed research by her and colleagues that has taught us about the planets around other stars in our neighborhood, in all their variety.

The stars are organized in galaxies, another subject of active research. Galaxies appear in concentrations ranging from groups of a few galaxies to clusters of hundreds of large galaxies. Groups and clusters tend to be concentrated in superclusters. But there is something new on still larger scales: observations reveal no higher layers of structure. We are instead presented with a universe that looks much the same everywhere and in all directions: a clumpy sea of galaxies and groups and clusters of galaxies. (A statistician might say the universe is well approximated as a stationary random process: fluctuations of the mass distribution around a fixed mean value have the same statistical character everywhere and in all directions.) This is why we can attempt to find a testable theory of the universe, rather than a theory of a level in a hierarchy of phenomena on larger and smaller scales.

Einstein had argued on philosophical grounds that it ought to be this way, before large-scale homogeneity was observed. In Einstein's vision inertial motion could be meaningful only relative to how matter in the neighborhood is moving. But his general relativity theory gives meaning to inertia even in an otherwise empty universe, provided it has a spacetime. To avoid what he considered to be philosophically unacceptable Einstein proposed a boundary condition: the universe has no edges, no preferred position. Einstein proved to be right. We still debate whether he was right for the right reason.

I must hastened to add that there certainly may be boundaries to the universe as we know it. This is a common conjecture among those exploring ideas about the state of the universe in the very remote past. The universe can be examined, in varying degrees of detail, by detection of radiation that has been traveling toward us since the early stages of expansion of the universe. We have only indirect hints to what lies beyond that, which certainly makes it difficult to check ideas. But within the region that can be observed is an abundance of phenomena. Typical sizes of superclusters are roughly one percent of the greatest distance we can observe. This is room for some million superclusters of groups and clusters to be studied in varying degrees of detail.

The first good evidence that the observable universe averages out to homogeneity came from the discovery that we are in a sea of hard X-rays, and soon after that that there also is a sea of microwave radiation (wavelengths of millimeters to centimeters, and now known as the Cosmic Microwave Background, or CMB). Both radiation backgrounds are very close to isotropic: coming at us at nearly the same intensity from all directions. This isotropy means either that we are close to the center of an inhomogeneous but spherically symmetric universe, or else that the radiation is close to homogeneous. The former seems quite unlikely. There are enormous numbers of other galaxies that seem to be equally good homes for us. If the universe were not close to homogeneous then our galaxy would be in an exceedingly special place, near the center of symmetry, and an observer in almost any other galaxy would see that the radiation backgrounds vary across the sky. The more reasonable notion is that an observer in any galaxy would see about the same thing, because the universe is filled with near homogeneous seas of X-rays and the CMB. The near homogeneity of the matter distribution is best tested indirectly, by the relativistic theory of how departures from a homogeneous mass distribution would perturb the distribution of the CMB. Measurements of the distributions of matter and the

CMB are found to be consistent under the assumption of general relativity theory. This also means that general relativity passes a demanding test.

Georges Henri-Joseph-Edouard Lemaître, a Belgian Catholic Priest and physicist, was the first to recognize observational evidence that the universe is expanding. I believe that in the years around 1930 Lemaître understood Einstein's general relativity theory better than anyone else. He also knew the astronomers' observations that the light from distant galaxies is shifted to the red, to longer wavelengths, as if the light had been Doppler shifted by motions of the galaxies away from us. And he showed that this behaviour is to be expected if the universe is homogeneous and expanding. He recognized that general relativity predicts that a static homogeneous universe is unstable: the slightest disturbance sets it collapsing or expanding. The astronomers' redshifts say it is expanding.

Lemaître's expanding universe theory was based on observations, but not enough to make a serious scientific case for the expanding universe theory. More convincing evidence came from measurements of the intensity spectrum (the distribution of energy with frequency) of the CMB, the sea of microwave radiation. The results are summarized in Figure 1. The

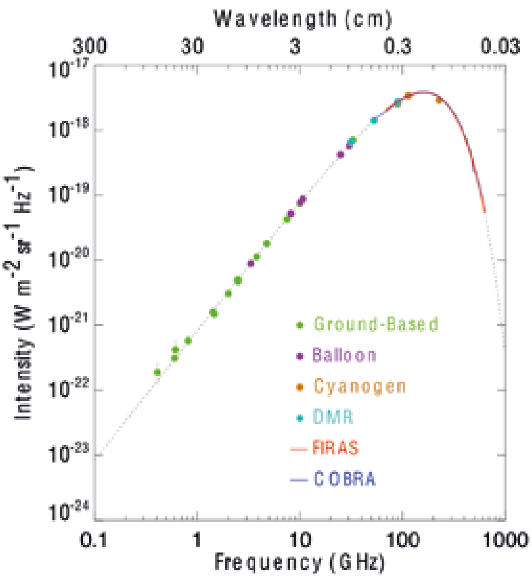

Figure 1. Intensity spectrum of the microwave radiation that nearly uniformly fills space. The dotted curve is the theory. The data points and the coloured curve near the peak are measurements that fit the thermal spectrum very well. From Kogut (2011).

thin dotted curve represents the intensity spectrum at thermal equilibrium. The coloured curve near the peak represents measurements, not theory. The symbols represent other measurements at discrete frequencies. The distinctive thermal shape of the measurements is what would be expected if this were a fossil remnant from an early state of expansion of the universe, when it was dense and hot enough to have relaxed to statistical equilibrium, which of course includes thermal radiation. Under standard local physics the expansion cooled the radiation, leaving it with the observed thermal spectrum at the present measured temperature, 2.725 K (measured above absolute zero).

It was natural to ask whether processes in the universe as it is now might have produced this thermal spectrum. But the universe as it is now is seen to be transparent at these wavelengths. No absorption means no relaxation to thermal equilibrium. The conclusion seems quite convincing: this radiation is a fossil left from when our expanding universe was dense and hot.

(In more detail, we may note that as the universe expanded this sea of radiation did not go away – in a homogeneous universe there is no place for it to go. Or perhaps better put: every photon moving away from us is on average matched by a photon moving toward us from afar. The expansion of the universe shifts CMB photons to longer wavelengths, and decreases the photon number density, which together conspire to preserve the thermal spectrum).

I count Figure 1 among the iconic images that succinctly represent great advances in natural science, here evidence that our universe is evolving.

Preservation of the thermal shape of the CMB intensity spectrum is expected under standard local physics if the expanding universe is close to homogeneous. But the preservation does not depend much on the rate of expansion of the universe. This means that the fact that the measured spectrum is close to thermal does not seriously test general relativity. This theory is tested by measurements of distances and redshifts. Saul Perlmutter discusses these measurements in these Proceedings. And relativity theory is tested in quite another way by comparison of the predicted and measured evolution of departures from homogeneous distributions of matter and the CMB. The measurements are far more precise and accurate than ever I imagined when I was working out these ideas in the early 1980s. And the theory fits these precise measurements.

(The situation might be described in a little more detail as follows. The theory predicts that small departures from homogeneity in the early stages of expansion of the universe tend to grow under the influence of gravity. But the hot state of the early universe would have ionized the matter, the free electrons would have scattered the thermal radiation, and that would have made matter and radiation act as a fluid. Fluids support pressure waves. The nature of the waves is controlled by boundary conditions. Thus the boundary conditions in an organ pipe set the fundamental tone, or wavelength. Boundary conditions for pressure waves in the expanding and cooling universe are set in time. When the universe had expanded and cooled to about 3000 K the plasma combined to neutral atoms. That rather abruptly set matter free from the radiation. The pattern of pressure waves at that point was imprinted on the matter and radiation. Gravity caused the matter waves to grow more prominent, eventually becoming galaxies and clusters and superclusters of galaxies. The radiation propagated to us more or less freely, presenting us with the measured slight anisotropy of the CMB).

There is an interesting complication. To make the predicted patterns of matter and the CMB agree with what is observed we must postulate that the ordinary matter of which we are made (so-called baryonic matter, after the baryons in atomic nuclei) is about one sixth of the total mass of the universe. The other five sixths is assumed to be a new form of matter that interacts weakly if at all with ordinary matter and radiation. This hypothetical component, known as dark matter, must behave at least roughly like an ideal monatomic gas with very low initial temperature. (The temperature remains low in a stream of this dark matter, but when orbits cross in growing mass concentrations the mix of orbits approximates a hot gas).

The fit of observed and measured distributions of matter and radiation also requires the presence of the cosmological constant, Λ. Saul Perlmutter describes in these proceedings how he and colleagues detected Λ, in quite a different way. That is, we have two quite independent lines of evidence pointing to the presence of Λ. This makes a strong case. And the agreement of theory and measurements of the distributions of matter and the CMB makes a strong case that general relativity gives a useful approximation to what happened.

2. The present situation

Our theory is incomplete. We do not know what the hypothetical dark matter is. We do not know why Einstein's Λ has a truly curious value in the context of what we now understand about fundamental physics. And we do not have much evidence about what the universe might have been doing before it could have been described by classical general relativity theory and the rest of conventional physics. But all physical theories are incomplete. Thus the theory of electromagnetism that Maxwell wrote down a century and a half ago is still taught, in better notation, because it is very useful. But this theory fails on the scale of atoms. It is now established that Maxwell's equations are a limiting case of quantum electrodynamics. This theory works very well through the scales of molecules and atoms and atomic nuclei and their contents. But what about the infinities of quantum electrodynamics? Perhaps some are the fault of the perturbative methods of computation. Perhaps others will be resolved by making quantum electrodynamics a limiting case of a still deeper theory, maybe superstrings. That calls for a lot more work to be done. The situation is similar in cosmology. Our present theory passes a considerable network of tests based on observational evidence of what happened from the time light elements formed, when the temperature was about $T \sim 10^9$ K, to the present, at $T = 2.725$ K. And the tests are dense enough to make a convincing case that the theory is a useful approximation, though incomplete.

The incompleteness of our theory of the large-scale nature of the universe is disappointing: we wish we had done better. But it is exciting: we may be sure the incompleteness is offering us hints to a better theory. It is a good bet that a better theory will contain elements that behave like dark matter, Λ, and all that, because the present theory fits a considerable variety of evidence of these components. But that is to be seen, of course.

There is the line of thought that our present theory of the large-scale nature of the universe is incomplete at least in part because the suitability of the universe for our existence is to be attributed to Intelligent Design. I rely on the expertise of George Coyne, SJ, and former director of the Vatican Observatory, who I quote, as accurately my memory allows, "Intelligent Design is bad science and bad theology". To observe and attempt to make sense of the material world in which we find ourselves is good science, and I trust acceptable theology.

Scientists whose judgements I respect argue that our present standard theory may be incomplete in part because it does not take account of the Anthropic Principle. This supposes a multiverse, an unlimited variety of universes with different properties, including different and various laws of physics. Or else there is one universe in which well-separated parts are quite different. We must find ourselves in a universe, or a part of the universe, that has properties consistent with our existence. So is our universe thus selected from an ensemble to fit our needs? Or instead are we selected to live with what the universe offers? There are good arguments for the former. But I am uneasy about the freedom to decide when to invoke the Anthropic Principle. In effect, shall we be tempted to give up on some particularly challenging issue and declare that "then something magic happens"?

It certainly is right and appropriate to marvel at how well our environment suits our needs. This is in part a consistency condition. Our species became organized when conditions allowed it: Earth's climate has been relatively stable and benign since the last ice age, allowing agriculture to flourish and support other organized activities. This is an eventuality. Other conditions are fixed by physics. It is a Good Thing for us that ice is less dense than water, for if ice sank as it formed it would be much less likely to melt in the summer, maybe turning planet Earth into a permanent snowball. But in an imaginary alternative universe in which ice sinks while the physical situation otherwise is much like ours I imagine conditions suitable for us could obtain on a planet that has a greater abundance of radioactive elements. Greater internal heating by radioactive decay would be a greater source of heat to melt deep-sea ice. A more demanding Good Thing is that atomic nuclei are bound, though just marginally. A hypothetical universe with slightly weaker nuclear forces would contain only the lightest element, hydrogen. If physical conditions were otherwise similar to ours then gas spheres with the masses of planets and stars and larger would form and cool on Kelvin-Helmholtz time scales, millions of years. Molecular hydrogen would form by catalysis by free electrons, and I suppose molecules would form snowflakes of some kind. The familiar ones are interestingly complex. Might much more complex hierarchies of complex structures of the vapour, liquid, and solid phases of atomic and molecular hydrogen form, in millions of years, in many repetitions of the experiment, in the vast number of gas spheres in the vast number of galaxies in this universe? In short, the Anthropic Principle takes it that "beings" complex enough to change the environment, such as people on bulldozers, or sheets of bacteria, require conditions not vastly different from ours. But I suspect our imaginations are too limited to sort through all situations capable of something deeply complex, in our universe or a multiverse.

I am impressed by the vast number of planets in our observable universe. Lisa Kaltenegger explained the evidence that there are at least as many planets moving around stars as there are stars. In a large galaxy such as ours there are some 10^{10} stars roughly like the sun. There are roughly 10^{10} large galaxies in our observable universe, which means at least $\sim 10^{20}$ planets. Conditions on or in most of these planets surely are quite inappropriate for us. But if one planet in a million offered a suitable home for beings capable of something deeply complex it would mean our observable universe has on the order of 10^{14} potential homes. Why such an immense number? Do we ascribe this to the Anthropic Principle? Surely a galaxy or two would do for us.

Despite my unease about the Anthropic Principle I must agree that a universe with $|\Lambda|$ large enough to prevent anything much to happen at the rates set by the rest of the physics in that universe would not produce anything interesting. If Λ truly is a free parameter then we do require something outside our present and envisioned physics, perhaps some version of the Anthropic Principle. But one might imagine that a deeper fundamental physics to be discovered will predict an effective Λ whose present value and rate of change are consistent with what is observed. I hope the community will not give up pursuing this dream, and all the many other attempts to understand what to make of our physical universe as we find it.

The Figure and Legacy of Msgr. Georges Lemaître

Thomas Hertog

At this Special Session on Cosmology on the occasion of the 50th anniversary of the death of Msgr Georges Lemaître, we sketch the scientific, historical and personal context behind his pioneering contributions to our modern theory of cosmology. This provides also, indirectly and from a particular angle, a certain understanding of his position and his actions as President of this Academy (1960-1966), where he found so much a home.

The history of modern cosmology can roughly be divided into six periods, which take us from the first explorations of Einstein's static universe starting in 1917 to the precision science we have today. Lemaître's contributions must be situated in the second, crucial period from 1927 to 1939 in which the basic framework of modern cosmology was developed.

Lemaître himself traces his interests in science and cosmology to his childhood years he spent in and around the city of Charleroi in the South of Belgium. Unfortunately, World War I intervened and, like so many of his contemporaries, Lemaître signed up to join the Belgian army to defend his country. After the War he entered the seminary for the priesthood and he was ordained as a priest in 1923.

In the seminary, Lemaître was granted special permission by Cardinal Mercier to study Relativity, Einstein's new theory of gravity. He wrote a dissertation on Einstein's new physics and his ideas on cosmology. On the basis of this work the Commission for Relief in Belgium, under the auspices of the American Educational Foundation, awarded Lemaître a fellowship to study abroad. That was the beginning of a unique scientific adventure.

He first went to the University of Cambridge where he deepened his knowledge of Relativity under the guidance of Lord Eddington, one of the foremost astronomers at the time. It is likely that the confluence of Eddington's interests both in the theory of Relativity and in astronomical observations has encouraged Lemaître to explore himself their intersection in his later work. Lemaître and Eddington had great admiration for each other. Later Eddington would write (in a letter to de Donder, Lemaître's mentor in Belgium) that he had found in Lemaître "a truly brilliant student, wonderfully quick and clear-sighted and of great mathematical ability". Coming from Eddington this really meant something!

In 1924 Lemaître went on to MIT and to the Harvard College Observatory to work with Shapley on Cepheids, variable stars. The timing of this visit was excellent because during that year the first observations which would challenge the age-old idea of an everlasting, static universe would be coming in. Lemaître was present e.g. at the celebrated 33rd meeting of the American Astronomical Society held in Washington in December 1924 where Russell announced Hubble's discovery that the great spiral nebulae are in fact other, distant galaxies. It is during this year that we also find Lemaître's first explorations of cosmology. He studied in particular the model of the universe proposed by the Dutch astronomer de Sitter – which incidentally was disguised as a static universe - and he showed, independently from Weyl, that in de Sitter's universe galaxies would recede from each other at a rate proportional to their separation. Starlight from distant galaxies would therefore be shifted to the red in de Sitter's universe, in line with the observational evidence at the time. But de Sitter's universe is empty, it contains neither galaxies nor observers! Therefore Lemaître abandons this model.

In July 1925 Lemaître returned to Belgium to take up a faculty position at the Catholic University of Louvain. He continued to think about cosmology, and wondered in particular whether Relativity could accom-

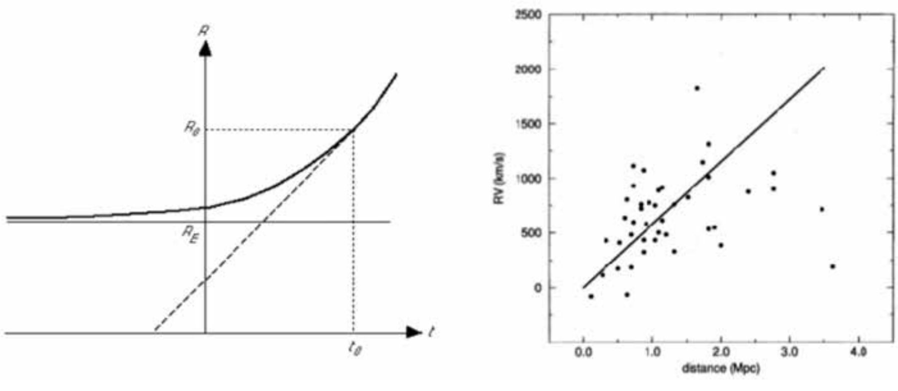

Figure 1. Left: Lemaître's first model of 1927 of a dynamical universe, in which an expanding universe emerges from a nearly static Einstein universe in the far past. The radius *R* increases in time *t* from a finite value *RE* in the infinite past. Right: the observations of extra-galactic nebulae that Lemaître used to verify the distance-velocity relation he had derived in this model.

modate a universe that retains the appealing features of both Einstein's static universe and de Sitter's empty universe. A universe, in other words, that contains matter in the form of galaxies but at the same time exhibits the reddening of distant galaxies. Lemaître's stroke of genius then was to abandon the idea of a static universe. He did so in 1927 in a seminal paper *Un univers homogène de masse constante et de rayon croissant, rendant compte de la vitesse radiale des nébuleuses extragalactiques*, which he chose to publish in the Annales de la Société Scientifique de Bruxelles [G. Lemaître, 1927].

In this paper Lemaître first rediscovers Friedmann's equations that govern the evolution of a dynamical universe in Einstein's theory of Relativity. He then identifies a solution of those equations that describes an expanding universe interpolating between Einstein's static universe in the far past and de Sitter's empty universe in the distant future [cf Figure 1]. He shows further that if this were our universe then the expansion of space would cause starlight from distant galaxies to be shifted to the red, as if the light were Doppler shifted by the motion of galaxies away from us. Lemaître derives (in equation (24) in [G. Lemaître, 1927]) what would later become known as the Hubble law; a linear relation between the rate of separation of distant galaxies and their distance away from us. Moreover, seeking observational corroboration or falsification for his prediction of a redshift, Lemaître takes Slipher's redshifts and Hubble's distances for a sample of 42 extra-galactic nebulae to estimate the proportionality constant H in the distance-velocity relation. Because of the large uncertainties in the individual observations, particularly in the distances, Lemaître decides to divide the mean velocity by the mean distance in the sample, and in this way obtains the value H=575 km/s per Megaparsec.

In short, Lemaître establishes in this paper *the* fundamental connection between the theory of Relativity and cosmology. He himself once recalled, in his characteristic light, humble style, that "I happened to be more mathematician than most astronomers, and more astronomer than most mathematicians".

However, most of the important figures in cosmology hardly took notice of Lemaître's groundbreaking work, and the few remarks that did reach Lemaître, were actually mostly negative. In the margin of the 1927 Solvay Conference, for instance, Lemaître had a brief discussion of his work with Einstein, who concluded this by saying "Your calculations, Monsieur Lemaître, are correct, but your physical insight is *tout à fait abominable*". Clearly the scientific community was not (yet) prepared to abandon the ancient, cherished idea of an eternal, static universe.

But in 1929, Hubble established observationally a linear distance-velocity relation for the spiral nebulae. Using more precise observations of 24 distant extra-galactic nebulae obtained with the 100-inch telescope on Mt Wilson, the most powerful telescope at the time, Hubble obtained a proportionality constant of 513 km/s per Megaparec – not very different from the value found by Lemaître two years earlier. Hubble's work made no mention of the expansion of the universe. Instead he interpreted his observations in terms of a usual Doppler shift. But the scientific community recognised the potentially far-reaching implications of Hubble's observations and in particular the need to reconcile these with Relativity if the latter were to provide a viable theoretical framework for cosmology.

The problem of the reddening of distant nebulae was therefore high on the agenda at the London meeting of the Royal Astronomical Society on Friday, 10 January 1930, where Eddington famously said "We ought to put a little motion into Einstein's world of inert matter, or a little matter in de Sitter's primum mobile". Georges Lemaître was not present at this meeting, but when he read its proceedings in *The Observatory* a few weeks later he responded and reminded Eddington that two years before he had already found the intermediate, expanding solution that he and de Sitter were now looking for [cf Figure 2]. Lemaître also enclosed several copies of his original paper with his letter and asked Eddington to give one to de Sitter.

Eddington confessed that, although he had seen Lemaître's pioneering paper at the time, he had failed to realise its far-reaching consequences and he had forgotten about it until that moment. Around the same time Eddington himself independently showed that Einstein's static universe is unstable to either expansion or contraction. He was thus ready to adopt Lemaître's model of 1927, which became known as the Eddington - Lemaître universe.

Starting in May 1930 both Eddington and de Sitter generously recognised Lemaître's major discovery in their publications, and they enthusiastically supported and disseminated the new concept of an expanding universe. In 1931, in an extraordinary sign of appreciation that shows the importance he attached to Lemaître's work, Eddington ordered a translation of Lemaître's original paper to be published in the widely read Monthly Notices of the Royal Astronomical Society (MNRAS) [G. Lemaître, 1931].

But then something seemingly odd happened. The section in the original paper where Lemaître derives the 'Hubble constant' *H* was omitted in the translation, and replaced by a short note referring to 'available data'.

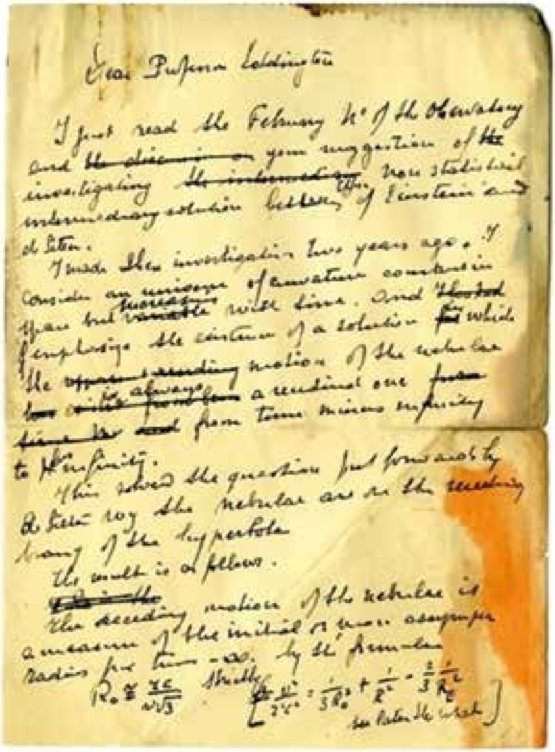

Figure 2. The first draft page of Lemaître's letter in which he tells Eddington that two years before he had found the expanding solution Eddington was looking for. [source: Archives Georges Lemaître, Université catholique de Louvain, Louvain-la-Neuve.]

This has led some historians to suggest Lemaître had been censored – perhaps even to advance Hubble's reputation?

However the case was settled in 2010 thanks to a careful investigation by Livio, who found in the archives of the Royal Astronomical Society a letter from Lemaître to Smart, the editor of the MNRAS, in which Lemaître writes that "he did not find advisable to reprint his provisional discussion of radial velocities". Lemaître's motivation to leave out this particular section was most likely that the uncertain observational material available in 1927, which nevertheless convinced him of the validity of his theoretically derived 'Hubble law', had by 1931 been superseded by better data from Hubble and Humason. And, of course, Lemaître was not interested in self-promotion.

The translation of Lemaître's article in the MNRAS had a large impact, and his idea of an expanding, evolving universe rapidly became the central pillar of modern relativistic cosmology. Finally also Einstein came around. In the short article in which he accepted the expanding universe Einstein also discarded the idea of a cosmological constant, which he had introduced in his equations in 1917 to make possible a static universe. In a letter to Tolman he wrote "Dies ist wirklich unvergleichlich befriedigender", referring to his theory of Relativity without the cosmological constant term.

Interestingly Lemaître had a rather different view on the cosmological constant. Lemaître regarded this as a physical substance, known today as dark energy. Consequently 'little lambda' (as the cosmological constant was referred to at the time) featured prominently in Lemaître's work on cosmology. The first known representations of an expanding universe, made by Lemaître around 1928, clearly illustrate this [cf Figure 3]. Around 1931 Lemaître settled on what he called a 'hesitating' universe. This is a universe which initially expands fast, then slows down so that large-scale structures

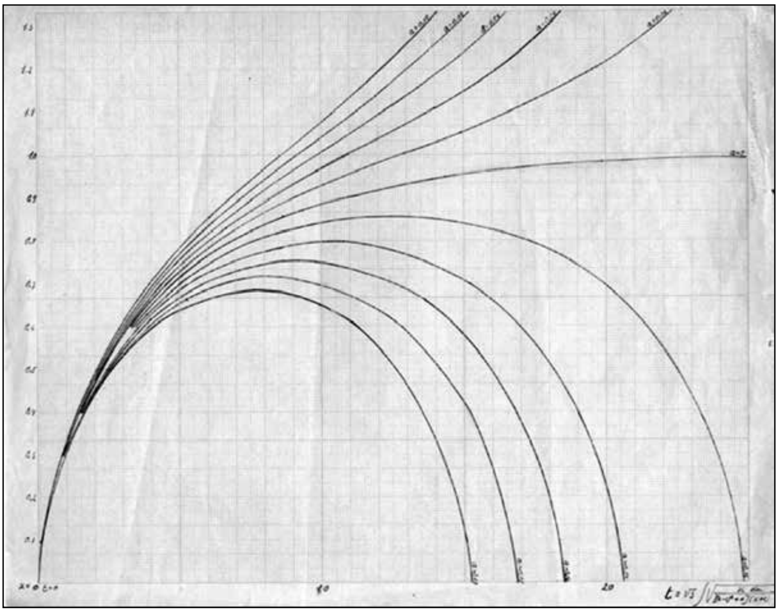

Figure 3. Shown are a range of possible dynamical universes according to the theory of General Relativity, drawn by Lemaître in 1928. Lemaître includes the effect of a cosmological constant term on the universe's evolution which causes some universes to expand forever. [source: Archives Georges Lemaître, Université catholique de Louvain, Louvain-la-Neuve.]

such as stars and galaxies can form, and finally accelerates again, driven by the effect of a dark energy component. Being much more than Einstein guided in his work by observations, Lemaître was led to the idea of a 'hesitating' universe with a cosmological constant, because the large value of the Hubble constant which he and Hubble had found, implied there had to be a preceding era of slower expansion in order for the universe to be old enough to harbour stars and galaxies at least as old as planet Earth. He maintained this vision of cosmological evolution – which is in excellent agreement with present-day precision observations – for the rest of his life.

Lemaître's hesitating universe also introduces a profoundly new feature in his cosmology: it replaces the nearly static phase in the far past of his original model of 1927 with a genuine origin. He referred to the state at the beginning as a primeval atom. (The term Big Bang was coined much later by Fred Hoyle). By boldly proposing the world had a beginning Lemaître made it clear that a universe in expansion may well have been in a radically different physical state in the far past. The notion of a cosmic evolution is central in Lemaître's thinking. He explained his view in what is perhaps his most visionary article *The Beginning of the World from the Point of View of Quantum Theory*, published in *Nature* in 1931 [G. Lemaître, 1931b]. In this short paper he argues, to my knowledge for the very first time in the history of modern cosmology, that our universe had an origin which should be part of science, governed by physical laws we can discover. It is a beautiful, almost poetic paper in which Lemaître explores from a purely physical viewpoint how our universe could have come into existence - a question that would become one of the central research topics in the fields of quantum gravity and quantum cosmology more than half a century later.

Of course Lemaître did not put forward a theory or even a model for his primeval atom. In Relativity the origin of an expanding universe is a spacetime singularity where our usual notions of space and time cease to be meaningful, and Einstein's theory breaks down. Lemaître realised this, but suggested space and time emerged from a more fundamental, abstract quantum mechanical state which, he argued, stands prior to space-time. In line with this view he regarded the beginning as a kind of horizon beyond which lies a realm of reality that neither influences our observable universe nor will ever be accessible to our observations. In a sense Lemaître's primeval atom acts as a boundary between physics, and metaphysics.

Incidentally Lemaître was led to consider a quantum origin of the world partly because he thought there should be a 'natural' beginning, and he reasoned that the indeterminacy of quantum theory could provide a potential mechanism to generate a complex universe from a set of elegant and simple initial conditions. Today this idea is realised concretely in inflationary cosmology where the rapid expansion transforms the simplest initial state – the quantum vacuum – into the seeds of the complex configuration of large-scale structures we find in today's universe.

Lemaître realised however that a fuzzy quantum origin does not give rise to a unique world. Contemplating the implications of this, he wrote "Clearly the initial quantum could not conceal in itself the whole course of evolution. The story of the world need not have been written down in the first quantum like the song on a disc of a phonograph ... Instead from the same beginning widely different universes could have evolved" [G. Lemaître, 1931b] – a worldview not unlike what today we call the multiverse.

In the light of Einstein's reluctance to accept cosmic evolution it will come as no surprise that he was not happy with Lemaître's hypothesis of a primeval atom. Ironically he even complained to the Belgian priest that this reminded him too much of Christian dogma, whereas Lemaître was making the case for a scientific inquiry of the universe's origin.

Despite their differences, however, in the early 1930s Lemaître and Einstein interacted frequently with each other. Their discussions were friendly and stimulating. During these years Lemaître spent several terms in the United States, where he wrote a number of highly influential articles in which we find the seeds of many of the ideas that later became part of the standard model of relativistic cosmology. These include the construction, inspired by Tolman's work, of the first (spherical) models of the formation of galaxies in an expanding universe, and an interpretation of the cosmological constant as a vacuum energy. In response to a question from Einstein, Lemaître also demonstrated that under certain conditions a beginning of time is unavoidable in Relativity. This result would be proven in full generality by Hawking and Penrose only in the 1960s, and it emphasises the quantum mechanical nature of Lemaître's primeval atom. Finally in 1934, he suggested there should exist fossil relics of the hot dense state of the universe at early times, which might allow us to trace back our history and "reconstruct the vanished burst of formation of the worlds" as he put it.

Meanwhile Lemaître had become the darling of the American press. The public discovered to its amazement that the 'father of the big bang' was also a Catholic priest. Lemaître, however, patiently explained why he saw no conflict between what he called 'the two paths to truth' that he decided, at a very young age, to follow. "Once you realise", he argued, "the Bible does not purport to be a textbook on science, and once you realise

Relativity is irrelevant for salvation, the old conflict between science and religion disappears". [cf Figure 4]

Lemaître carefully maintained a clear distinction between science and religion throughout all his life, respecting meticulously the differences in methodology and language between both. Far from the concordist interpretations that sought to derive the truths of faith from scientific results Lemaître insisted that science and religion have their own autonomy. He set out his position clearly and eloquently in his rapporteur talk at the Solvay Conference on Astrophysics in 1958 in which he emphasized once more that the hot big bang model is nothing but a scientific hypothesis, to be verified or falsified by observations, which remains entirely outside the realm of metaphysics or religion.

Consequently, Lemaître was not amused with the *Un'Ora* address of Pope Pius XII to this Academy in 1951, in which the Pope suggested that modern cosmology gives credit to the doctrine of *ex nihilo* creation at

THE NEW YORK TIMES MAGAZINE, FEBRUARY 19, 1933. 3

LEMAITRE FOLLOWS TWO PATHS TO TRUTH

The Famous Physicist, Who Is Also a Priest, Tells Why He Finds No Conflict Between Science and Religion

By DUNCAN AIKMAN

PASADENA.

"THERE is no conflict between religion and science," the Abbé Lemaitre has been telling audiences over and over again in this country and then proving it by explaining the aims of both. His view is interesting and important not because he is a Catholic priest, not because he is one of the leading mathematical physicists of our time, but because he is both. Here is a man who believes firmly in the Bible as a revelation from on high, but who develops a theory of the universe without the slightest regard for the teachings of revealed religion on genesis. And there is no conflict!

Such an attitude would have been preposterous to a Victorian physicist. Either you accept the whole Book of Genesis and therefore shut yourself out of the world of science, or you accept science and repudiate the prophets as expositors of the manner in which the universe began. Today the physicist is meeker. Behind his formulas there is something that is still veiled. He is half mystic and ready to admit that the universe may reveal itself in other ways than in mathematical equations or the bands and lines of a spectograph. The abbé, therefore, follows the trend of modern thinking and derives from it more than ordinary satisfaction because he happens to be trained in theology as well as in mathematical physics.

Lemaitre, like Eddington, finds that science and religion supplement each other. Science can never study the universe as a whole. It selects a small portion, as much as it can handle, and then makes deductions. To a cosmologist the earth and Mars are only planets wheeling around the sun. Are they inhabited? Are they washed by air and water? Why were they created? Is there purpose in the universe? Science is indifferent to such questions, but not religion.

that there must be authentic religious dogma in the binomial theorem. Nevertheless a lot of otherwise intelligent and well-educated men do go on believing or at least acting on such a belief. When they find the Bible's scientific references wrong, as they often are, they repudiate it utterly. Should a priest reject relativity because it

that it took perhaps ten thousand million years to create what we think is the universe. Genesis is simply trying to teach us that one day in seven should be devoted to rest, worship and reverence—all necessary to salvation."

"And that story about Jonah and the big fish?

"I admit that a whale cannot

powers with which they are credited in the Bible.

"If scientific knowledge were necessary to salvation," he says, "it would have been revealed to the writers of the Scriptures and they would have set it down in their verses. For instance, the doctrine of the Trinity is much more abstruse than anything in relativity or

question of salvation. On other questions they were as wise or as ignorant as their generation. Hence it is utterly unimportant that errors of historic and scientific fact should be found in the Bible, especially if errors relate to events that were not directly observed by those who wrote about them. The idea that because they were right in their doctrine of immortality and salvation they must also be right on all other subjects is simply the fallacy of people who have an incomplete understanding of why the Bible was given to us at all."

Lemaitre tells of a classroom scene in which he figured. An old father was expounding at the desk. Before him sat the lad who was to discover the expanding universe and who, even then, was brimful of science. In his eagerness the lad read into a passage of Genesis an anticipation of modern science.

"I pointed it out," says Lemaitre, "but the old Father was skeptical. 'If there is a coincidence,' he decided, 'it is of no importance. Also if you should prove to me that it exists I would consider it unfortunate. It will merely encourage more thoughtless people to imagine that the Bible teaches infallible science, whereas the most we can say is that occasionally one of the prophets made a correct scientific guess.'"

* * *

THERE is, the abbé admits, a varying sense of conflict between science and religion in the different branches of science. "The biologists seem to have peculiar difficulties," he reasons. "There is every reason for this. They have only recently discovered a few guiding laws and principles. Hence, in the past their studies have been confusing rather than enlightening. In a way their subject-matter has been gross.

"But give the biologist more laws like those of the Abbé Mendel and a new spirit is bound to awaken. The sense that this is a morally

Figure 4. The 'father of the big bang' maintained a clear, but not dogmatic, distinction between science and religion which he likened to 'two paths to truth'.

the beginning of time (without, however, explicitly referring to Lemaître's work). In the early 1960s Monsignor Lemaître, as President of the Pontifical Academy of Sciences, would strive to maintain the autonomy of the Academy to avoid any such mixing of science and theology. His methodological purity put him in an excellent position to advance the Academy's goals of fostering excellent science while maintaining a healthy relation with the Church.

Does this mean that in Lemaître's view cosmology has absolutely no meaning for philosophy or theology, or vice versa? Not exactly. Lemaître himself certainly experienced a deep unity between his spiritual and professional life, and I am tempted to think that the harmonious coexistence of his cosmology and his faith, not at a conceptual level but rather through his actions and initiatives, may well have been an important source of inspiration and creativity that led him to conceive of a universe in evolution, with an origin. We can find a hint of such a unity in the last paragraph of the manuscript of the article [G. Lemaître, 1931b] – crossed out before publication – in which he put forward his 'primeval atom' hypothesis. In this, he writes "I think that everyone who believes in a supreme being supporting every being and every acting, believes also that God is essentially hidden and may be glad to see how present physics provides a veil hiding the creation". Indeed a constant theme in Lemaître's theology was Isaiahs notion of Deus Absconditus. A hidden God, hidden even at the beginning of the world. Lemaître's physical description of the emergence of space and time from a primeval quantum respects the transcendence of God and, correspondingly, the autonomy of the world.

When the second World War engulfed the continent Lemaître stayed in Belgium where he focused on the needs of his students and tried to comfort his family and friends. During this period he was cut off from his international contacts and became scientifically isolated. He did not participate in the further development of the big bang model after the war, leading e.g. to Alpher's and Gamov's understanding of primordial nucleosynthesis and to the prediction by Alpher and Hermann of a thermal relic radiation of the hot big bang. Instead, Lemaître devoted most of his time to numerical computation, an old passion of him dating back at least to his time at MIT in the late 1920s. He famously called upon his students to carry a Burroughs E101 (one of the first electronic computing machines) which he had seen at the World Expo in Brussels in 1958, up to the attic of the physics building in Leuven, thereby establishing the university's first computing centre.

But observations that could vindicate Lemaître's hot big bang hypothesis remained elusive even in the 1950s. In those years his cosmology was actually not seldom regarded as old fashioned science that had been pursued in a spirit of concordism, his critics would say, and a rival theory, the steady state model of Bondi, Gold and Hoyle, entered the stage.

Lemaître's fortunes turned around in 1964 with the discovery of the cosmic microwave background by Penzias and Wilson and its cosmological interpretation by Dicke, Peebles, Roll and Wilkinson as remnant radiation of a hot Big Bang. Lemaître heard about this discovery on the 17th of June in 1966, a mere three days before his death, in the hospital, where a close friend brought him the news that the fossil relics that prove his theory right had finally been found. Lemaître replied 'Je suis content... maintenant on a la preuve'.

Bibliography

[G. Lemaître, 1927] *Un univers homogène de masse constante et de rayon croissant, rendant compte de la vitesse radiale des nébuleuses extragalactiques*, G. Lemaître, Annales de la Société scientifique de Bruxelles, Série A, 47, 49-59 (1927).

[G. Lemaître, 1931] *A homogeneous universe of constant mass and increasing radius accounting for the radial velocity of extra-galactic nebulae*, G. Lemaître, MNRAS, 91, 490-501 (1931).

[G. Lemaître, 1931b] *The beginning of the world from the point of view of quantum theory,* G. Lemaître, Nature, 127, 706 (1931).

Role of Space Technology for Enabling Inter-Generational Equity of Natural Capital and Disaster Resilience: Corollaries of Indian Space Programme

Kasturirangan, K. and John Mathew[1]

1. Introduction

Since the introduction of the sustainable development concept in 1980 by International Union for the Conservation of Nature and Natural Resources (IUCN, 1980), the idea has been widely discussed (Allen, 1980; Goodland and Ledec, 1987; World Bank, 1987). It is about meeting the needs of the present, without compromising the ability of future generations to meet their own needs (WCED, 1987), in addition to the economic dimension (Peezey, 1992). Sustainable development will enable securing food, water, energy and environment for future generations, through optimal utilization of natural capital and its equity across generations. Sustainability also implies managing natural hazards and diseases, towards better survivability for evolving disaster resilient and healthy societies.

The sustainable development goals (SDGs) set by the UN specifically address the utilization of natural resources in productive and non-degrading manner, utilization of renewable energy, combating the impacts of climate change and developing safe & disaster resilient habitations towards ending poverty, providing food; water; health & shelter security, achieving economic growth, development and sharing prosperity (World Bank, 2016). Out of the 17 sustainable development goals, 11 of them have direct reference to natural resources, environment, climate change induced impacts, disaster resilience and health, implying the importance of these factors in achieving sustainable development and amenable to the use of space systems.

The sustainability of many natural resources is measured using suitable indicators (World Bank, 2016). These indicators include long term trends of arable land (as percentage of land area or per capita), agricultural land (% of land area), forest area (% of land area), surface water (fresh), dynamic

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ground water, energy utilization (from hydrocarbons, renewable sources & nuclear), atmospheric pollution (CO_2, NO_X, $PM_{2.5}$), climate change induced impact (sea surface temperature increase, sea level rise, glacier retreat, polar ice fragmentation), etc.

Some of the indicators of development present a picture that is contrary to the notion of sustainability. For example, based on the database of development indicators presented by World Bank, the per capita arable land has decreased by 47% during the last 5.5 decades. With considerable share of fossil fuels for energy production (nearly 80%), GHGs have increased by 95% during the last four decades. Periodic monitoring of the state of natural capital and indicators of climate change are necessary to make sure that the development is sustainable. Natural disasters and extreme weather events cause extensive damage every year and the global economic loss estimated by EM-DAT amounts to $2600 Billion during 1994-2013 (CRED, 2015). Space Technology provides necessary data to estimate the status of natural resources & environment, to model climate change and study its impact and to reduce the risk from natural disasters. It helps decision makers to introduce policy interventions for managing development, in a sustainable way, provides input for disaster risk reduction and enables access of health care for population in remote and far-flung regions.

2. Role of Space Technology in Sustainable Development

Spaceborne systems are capable of recording the reflected or emitted energy from earth's surface and atmosphere, in EM wavelengths spread across Visible to Microwave regions, with half hourly observational frequency from Geostationary platforms to as fast as 24-hour revisit capability from Sun-synchronous orbits and with spatial resolution ranging from about 30 cm to 50 km.

Geospatial technology comprising of spatially referenced data from Earth Observation and from other sources, Geographic Information System for managing such data, and location-based services from Global/Regional Navigational Satellite Systems (G/R-NSS) are widely used today for addressing various aspects of sustainable development. The recorded energy from Spaceborne systems, integrated with ground based information helps to derive spectral characteristics of the targets to quantify their areal or linear extent, chemical composition, indices linked to their spectral absorptions and also to estimate bio/geo-physical or chemical parameters of Earth Systems. Such measurements directly or as input to models which derive, specific products related to land, ocean or atmosphere and climate change, help policy makers to take informed decisions to ensure security of food, water, energy or environment, and to mitigate disaster risk and climate change induced impacts.

Concurrent use of high spatial & temporal resolution Remote Sensing, positional information from G/R-NSS and ground based inputs help planning expansion and intensification of cultivation, water stress / land degradation monitoring, soil nutrient and agricultural pest management, planning and monitoring of irrigation infrastructure, provision for agro-meteorological & potential fishing zone advisories, monitoring of surface waterbodies and its aquaculture potential, groundwater prospecting & recharge infrastructure development etc. towards enabling food and water security. Spaceborne inputs are used for deriving assured solar energy potential, hydropower potential, wind and wave energy potential, towards achieving energy security. Satellite data derived weather parameters are used as input in forewarning of vector-borne diseases or satellite communication services are used for enabling tele-medicine facility.

Space technology helps to evaluate the quality of environment and ecosystem in terms atmospheric aerosol and chemistry, GHGs, biodiversity, deforestation, water quality and waste management. Space borne observations of atmospheric parameters such as temperature, humidity, cloud fraction, solar insolation as well as rainfall measurements provide input for weather research forecast models and for now-casting. Climate change induced impacts such as increase in sea surface temperature, glacier retreat, permanent snow cover reduction, polar ice dynamics, sea level rise and extreme weather events are also measurable or can be modelled for predicting future scenario. Out of the nearly 50 Essential Climate Variables (ECVs) (Bojinski *et al.*, 2014), nearly half are amenable to earth observation systems.

In the pre-disaster phase of the disaster management cycle, input from earth observation systems are used in hazard/risk assessment and development of early warning systems for flood, earthquakes, landslides and cyclone. Models using space inputs such as temperature, humidity, rainfall and land cover are used for Flood Forecast Modelling (Weather Research & Forecast coupled with Hydrological Model) and Cyclone Track Prediction (Hurricane Weather Research & Forecast / Lagrangian Advection Model) or Land Surface Temperature based Forest Fire Alerts. Thermal Infrared & Visible domain images and wind vectors are used in cyclogenesis and track prediction. During the disasters, the earth observation data provides images for rescue and relief operations, and tracks progression of the natural hazards like flood, cyclone etc. Satellite based emergency communication facilities are extremely helpful in coordinating search, rescue and relief operations. High-resolution remote sensing data is useful in assessing the damage caused by natural hazard to infrastructure, habitations, utilities, agriculture and forests. In short space based inputs are widely and effectively used in disaster management to enable the societies to become resilient to the disasters.

3. Indian Space Programme and its Contribution for Sustainable development

The prime goal of Indian Space programme is national development. The earth observation, communication and navigation programmes support the developmental activities by providing necessary data, products and services (Kasturirangan *et al.*, 1996). Currently, India has deployed 15 operational Communication satellites and 17 Earth Observation satellites for Atmosphere, Land and Water, both from Geostationary and Sun-synchronous orbits, in optical and microwave domains. The 7-satellite navigational constellation; NavIC is established, for which the first generation receivers are being tested. The current EO systems are capable of providing data with 0.62m spatial resolution; 14bits spectral resolution and 2.5-day temporal resolution. The data and products from India EO satellites are disseminated through online Data Distribution System, Bhuvan Geospatial Gateway, MOSDAC meteorological product gateway, SCORPIO cyclone early warning system and also to the National Meteorological Department.

The EO application projects, data products, services and dissemination mechanism are designed and developed to address the management of natural resources (monitoring, enhancement of output from their utilization and as input for decision making for food, water and energy security), utilization of renewable resources, monitoring of environment (quality of air; water; soil; forest, biodiversity etc.), weather and agrometeorological support, climate change impact assessment and decision support for disaster management.

3.1. Assessing the Status of Natural Resources

The Natural Resources Census (NR-Census) programme initiated by Indian Space Research Organisation (ISRO) carries out national level, periodic assessment of various parameters such as Land use / Land Cover, Forest, Soil, Geomorphology, Lineaments, Land Degradation, Wasteland, Wetland and Snow & Glacier, at intervals of 1 to 10 years. The intervals are aligned with national planning process and the rate of change of parameters.The land use and land cover information is generated at multiple scales (1:250K; annually and 1:50K; 5-yearly), The 1:50K land use / land cover layer is generated using 3 seasons' IRS Resourcesat-2 LISS-III data (Figure 1) with 54 classes at lowest level; Level-III (NRSC, 2012). It is used in the decision making for agricultural productivity enhancement, utilization of cultivable wastelands and fallow lands, watershed development, afforestation planning, coastal zone management and climate change research.

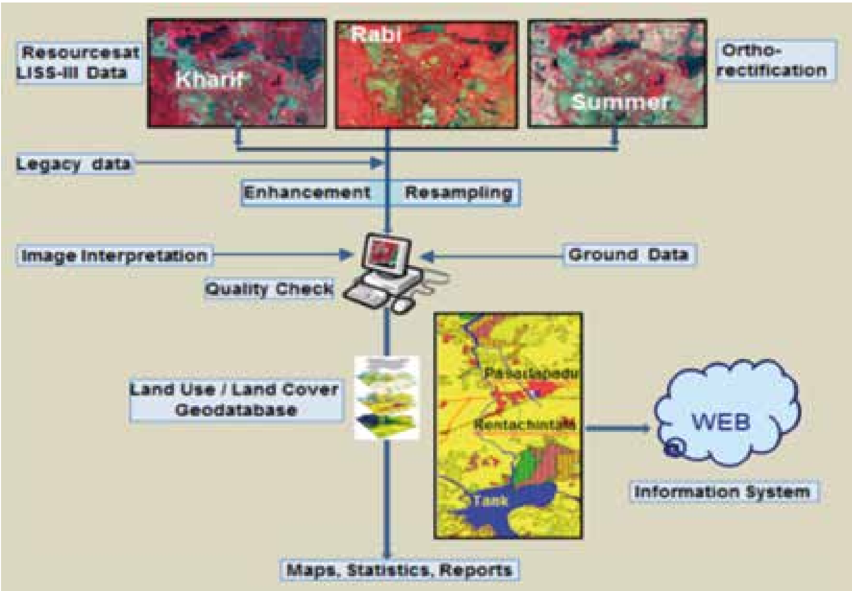


Figure 1. Natural Resources Census: Land use / Land Cover Mapping using multi-season Remote Sensing Data (Source: NRSC/ISRO).

3.2. Input for Enabling Food Security

India extensively uses Earth Observation based input for Agriculture related applications such as area estimation, production forecasting, pest and diseases detection and incidence forecasting, cropping system analysis, agricultural area expansion, crop intensification, horticulture area assessment and area identification for expansion etc. Potential fishing zone advisory and inland aqua-culture development are also being done for achieving food security.

ISRO initiated a national programme called FASAL (Forecasting Agricultural output using Space, Agro-meteorology and Land based observations), to address the uncertainties in production, distribution and marketing through informed decision making related to pricing and import-export policies. From the mid-season to pre-harvest stage of crop growth, satellite data is used for estimating the crop area and crop yield. FASAL programme has been institutionalized with the establishment of Mahalanobis National Crop Forecasting Centre (MNCFC) by the Ministry of Agriculture. Currently in-season, multiple, pre-harvest crop production forecasts are given for 8 crops covering 53.2% of total cropped area; 78.3% of food grain production in the country (Ray, 2016), in addition to production forecast for pulses in the Rabi season. Space inputs are also used for better horticulture development for 7 major horticultural crops, in about 185 districts; spread over 12 States, in India. The activities include area assessment, production forecasting, and decision support for horticulture development & management; such as area expansion and intensification, post-harvest infrastructure planning etc.

The potential fishing zone (PFZ) advisory is another programme that has been developed by ISRO and internalized by the concerned agency under Ministry of Earth Sciences for operational execution (http://www.incois.gov.in/MarineFisheries/PfzWebGis), currently benefiting nearly 0.3 million fishermen. The potential zones of fish aggregation are derived from space-derived inputs on Sea Surface Temperature (SST) and Chlorophyll. Prior information on the potential zones (latitude/longitude and the bathymetry) is disseminated in the form of maps and text to the fishermen community through multiple means (web, sms, digital displays etc.) which helps to reduce the time and fuel spent for the fishing activity.

Methodology is developed for assessing the suitability, potential and management measures of village water bodies for inland aquaculture development, as a source of protein rich food for population and also as an employment opportunity.

3.3. Enabling Water Security

Sustainable use of water from all sources, efficient irrigation systems and reservoir storage restoration etc. are important factors with respect to water security. ISRO has operationalised the use of earth observation input for irrigation infrastructure monitoring, assessment of irrigation potential created and utilized, periodic automated surface water spread extraction & waterbody information system, reservoir capacity estimation, development

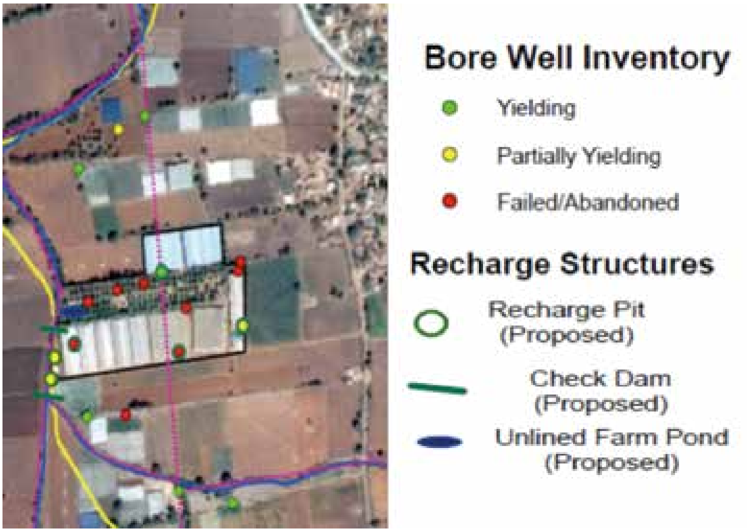


Figure 2. Inventory of existing wells, many of which failed, indicating over-exploitation and Planning recharge structures for ground water sustainability.

of hydrological information products, snowmelt runoff modelling, ground water prospects mapping and water resources assessment. A web-enabled, national information system of water resources; known as India-WRIS, has also been developed, with more than 100 spatial layers starting from vintage periods (~100 years) for decision making for water resources management (http://www.india-wris.nrsc.gov.in/wris.html).

The percentage of the districts in the country with more than 70% as ground water development stage (ratio of draft to available resource) as semi-critical to critical stage, has increased from 8 to 29 during 1995 to 2011 (Suhag, 2016). ISRO has implemented a national programme for identifying the prospective zones of ground water and locations of recharge structures. The methodology involved mapping the rock types, morphology and discontinuities using remote sensing and ancillary data, which influence the occurrence and movement of ground water, and then integrating these to derive composite units indicative of ground water prospects, in terms of expected yield and suggested depths of water. Locations of suitable recharge structures have also been identified so that, the ground water resources could be utilized in a sustainable way (Figure 2). A ground water information system for the country has been developed using this database and is available online on ISRO's Bhuvan geoportal.

3.4. Towards Achieving Energy security

It is necessary to explore and exploit the renewable resources to reduce the dependency on fossil fuels for energy. Evaluating the potential of solar, hydro, wave, geothermal and wind energy sources for their increased utilization in the national energy mix is the primary step towards this where space based inputs are used. In 2016 renewable energy sources contributed 39 GW of installed capacity (IEA, 2016) (13% of the total), mainly by wind (65%), solar (13%) and biomass (12%). The renewable installed capacity showed an increase of 23% during 2014 to 2015 where the installed capacity from solar energy showed nearly 85% increase during this period. This analysis shows that, though the fossil fuels contribute a major share of energy needs, there is focus towards enhanced utilization of renewable energy.

Instantaneous solar insolation is computed using spectrally integrated radiative transfer scheme and three-layer cloudy-sky model using satellite derived inputs such as cloud-top albedo, temperature, atmospheric water vapour, aerosol and ozone (Vyas et al., 2016), as input for solar energy harvesting. The estimates show that India receives assured annual global insolation up to 2500 $kWhm^{-2}$, with majority of Indian landmass receiving annual solar energy above 1750 kWh/m^2. Spaceborne scatterometer data-based wind energy potential and altimeter-data based wave energy potential have also been estimated, over the Indian seas. These inputs could be utilized for enhanced renewable energy utilization. Mobile Application has been developed for estimating location based solar energy potential, and model based wind energy potential, over India. 48-hour forecast of solar energy, is generated at every 15 minutes, which can be used as input for planning the energy grid operations.

3.5. Contributing for Environment and Health Security

Sustainable development also demands preserving the environment and ecosystem with respect to quality of air; water and soil, biodiversity, forest/ mangrove cover, coastline status, wetlands etc. Space borne data helps to discriminate the forest cover based on the crown density into multiple classes such as very dense (>70% crown cover density), moderately dense (70-40%) and open forest (40-10% crown density). The programme initiated by ISRO for assessing the forest cover using space technology has been internalized by the Forest Survey of India, the agency responsible for assessing the status of Forests in the country. Now, national level, biennial forest cover assessment is done for periodic evaluation of the forest cover. Further, ISRO has operationalized an automated methodology for detection of forest cover loss, using temporal integration of image pixels representing forested areas.

ISRO uses space data for mapping turbidity of water, salinity of soils, soil moisture, biodiversity, wetland spread and dynamics, coastal erosion status, coral reef morphology etc., which provide input towards decision making for ensuring environmental security. Air quality assessment using INSAT-3D/3DR data, based on aerosol optical depth, is also carried out, for monitoring purpose.

Access to quality medical consultation is enabled to people living in in-accessible and remote region using the tele-medicine concept. It connects the hospitals in the remote / rural regions and Mobile Units using Indian satellites to major specialty hospitals in cities and towns through customised medical software & hardware, and diagnostic instruments, connected to VSATs. Presently, around 130 Telemedicine nodes are operational across the country. Using output from weather forecast models and information on locations of waterbodies, land cover etc., forewarning on outbreak of vector borne diseases is also generated, for appropriate prior management measures.

3.6. Providing Information on Weather / Atmospheric parameters towards sustainable development

Information on atmospheric parameters has relevance in providing inputs for agro-meteorological models and services towards enhancing the food production. Measured atmospheric parameters form input to weather forecast models, for appropriate decision making on crop planning and also for disaster management with respect to extreme weather events. The measurement of weather parameters and keeping its records over long period of time is critical to understand the climate pattern and changes. ISRO's Meteorological and Oceanographic Satellite Data Archival Centre (MOSDAC) derives products from Atmospheric and Weather satellites' data. Nearly 30 products are generated every 15 minutes using the INSAT-3D & 3DR data. These products include short range forecast of temperature, relative humidity, cloud, wind and rain, now-casting of heavy rain and heatwave condition, sowing suitability for rice transplantation etc. The data from the atmospheric observation satellites also flow to the national meteorological organization for weather related advisories.

3.7. Monitoring of Climate Change induced impacts

The impact of climate change gets reflected in the form of extreme weather events (storms, cloudbursts, flood etc.), increase in sea surface temperature, recession of glaciers and decrease in permanent snow cover, fragmentation and reduction of polar ice, sea-level rise etc. ISRO formulated the National Information System for Climate and Environment Studies (NICES) with the mandate to build an information base for climate change impact assessment and mitigation (http://www.nrsc.gov.in/nices) by generating spatial & temporal blended Essential Climate Variable (ECV) products using space and in situ observations. About 52 climate/environment related variables across terrestrial, ocean, atmosphere and cryosphere domains have been generated and are available from the NICES geoportal. These include 13 ECVs also.

3.8. Disaster Management Support

ISRO's Decision Support Centre for Disaster Management addresses major natural disasters like flood, landslide, earthquake, forest fire, cyclone and agricultural drought, through early warning; hazard evaluation; (cyclone) track and landfall prediction; near-real time alerts; status updates and damage assessment, for enabling to move towards disaster resilience. It operates 24X7 providing timely input to the stake holders of disaster management in the country.

The flood situation in the flood prone regions of the country is monitored during the flood season through Optical and Microwave remote sensing data. Spatial flood early warning has been implemented in Godawari, Mahanadi, Brahmaputra and Barak valleys (covering 33 districts of Assam), using inputs such as forecast rainfall, flood inundation simulation using digital elevation from laser terrain mapping or spaceborne stereo data, modelled runoff and real time discharge data. The flood early warning system (FLEWS) in Assam has given an average year to year alert success score of 75% with alert lead time of 24 to 36 hours, since initiation.

Cyclogenesis (one to five days in advance), real time cyclone tracking and land fall prediction using Lagrangian Advection Track Prediction Model have been implemented as web based service; called Satellite based Cyclone Observations and Real-time Prediction over the Indian Ocean (SCORPIO), for timely evacuation in case of tropical cyclones. This had helped timely evacuation and saving precious lives during cyclone PHAILIN (2013), cyclone HUDHUD (2014) and cyclone VARDAH (2016, figure 3). Using thermal data from spaceborne sensors, forest fire alerts are generated six times daily and are disseminated to the Forest Department officials for ground validation and management measures. Landslide susceptibility assessment, automated landslide inventory from remote sensing

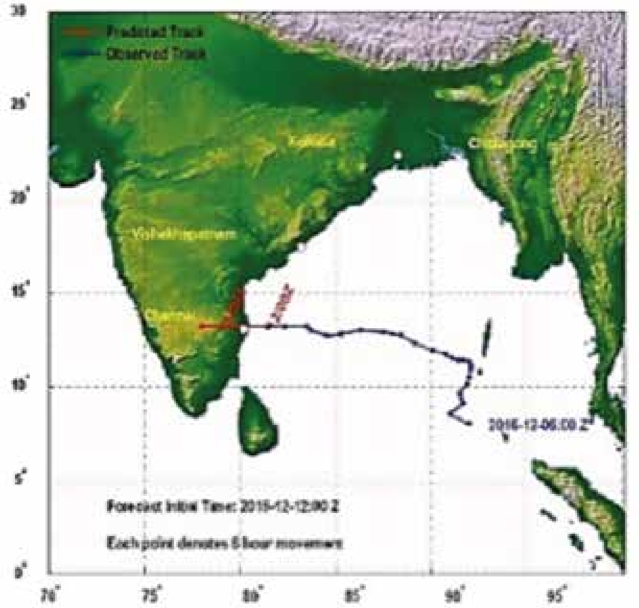


Figure 3. Cyclone track and landfall Prediction (24 Hour lead time) for Tropical Cyclone Vardah in December 2016 (Source: SAC/ISRO).

data and early warning for rainfall induced landslides are also implemented in ISRO's Bhuvan Geoportal.

Agricultural drought assessment is done based on satellite data derived indices such as Wetness, Vegetation, Soil Moisture and Shortwave Angle Slope (indicating surface moisture dynamics) and rainfall deviation from normal values for drought mitigation measures so that the agricultural production is not adversely affected. All these programmes and projects provide valuable input in disaster management towards evolving resilience and sustainable development.

4. Global Earth Observation Initiatives for Sustainable Development

Globally, the space faring nations have successfully demonstrated effective utilization of space based inputs for sustainable development in many aspects and have made collaborative efforts to achieve this. Global products on land cover, atmospheric chemistry, soil moisture, ocean salinity, etc. are generated by multiple space agencies under different programmes and are available for use in research or application programmes.

The intergovernmental organization called Group on Earth Observations (GEO) was set up in 2005 which envisions a future wherein decisions and actions for the benefit of humankind are informed by coordinated, comprehensive and sustained Earth observations. GEO facilitates the development of solutions to societal challenges by mobilizing resources including observations, science, modelling and applications, to enable end-to-end systems, in partnership with Global organizations like WMO, FAO etc. GEO's mission consists of establishing a Global Earth Observation System of Systems (GEOSS) as set of coordinated Earth observation, information and processing systems by facilitating the sharing of Space and ground data and processing tools for sustainable development, climate change impact reduction and disaster resilience (Source: Geo Strategic Plan 2016-2025-Implementing GEOSS).

5. Depending Outer Space for Sustainability on Earth

Enhanced capabilities in accessing outer space, technological advances and innovative thinking enabled scientists and entrepreneurs to explore the possibility to utilize space as an alternate source for resource and to develop business out of it. If this becomes a reality in a cost-effective manner, it will be one of the major achievements of humanity towards sustainable development. In terms of resources, mining near-earth asteroids that are rich sources of Nickel, Iron, Semiconductor elements, Platinum Group metals etc. is one of the possibilities being explored. Similarly, extracting and bringing Helium-3 from Moon is another idea which is relevant to energy security, for fusion based power generation, without producing radioactive waste. Extracting lunar water to generate liquid oxygen and hydrogen as space craft fuel is also an innovative idea that is being pursued by entrepreneurs. This can provide service to customers for launching inter-planetary and asteroid hunting missions from Lunar launch base.

Space based solar power generation is an idea which is being explored, and if successful, it will be a long-term solution for the ever-increasing energy requirements on Earth. The other dimension is about colonization of outer space, as a novel approach for sustainability of life on earth, such that, chance for survivability of the human species will be more, in the worst case scenario of mass extinction on Earth. Space entrepreneurs dream of making humans a multi-planetary species.

6. Conclusion

Space and space based observations offer wide range of input to support sustainable development. Space based observations on status of natural resources, and environment for informed decision making towards ensuring food, water, energy, environment and health security is the prime benefit of space input for sustainable development. Global space agencies as well as ISRO have implemented operational plans to capitalize on this aspect. Monitoring of weather and atmospheric parameters, climate change induced impacts and disaster management support are further aspects where space technology is being used for sustainable development. These help the present generation in judiciously utilizing the natural capital and making it available for future generations, while being resilient to natural disasters and diseases. Finally, outer space itself offers solutions which might become commercially viable, positively in about 5 decades or beyond, to address energy security and survivability threat on Earth.

References

Allen, R. 1980. How to save the world. *Strategy for World Conservation?* London: Kogan Page.

Bojinski, S., Verstraete, M., Peterson, T.C., Richter, C., Simmons, A. and Zemp, M., 2014. The concept of essential climate variables in support of climate research, applications, and policy. *Bulletin of the American Meteorological Society*, 95(9), pp.1431-1443.

Central Electricity Authority (CEA), 2016. Executive Summary, Power Sector, 41p.

Centre for Research on the Epidemiology of Disasters (CRED), 2015. *The Human Cost of Natural Disasters*, 55p.

DeSA, U.N., 2013. World population prospects: the 2012 revision. Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, New York.

International Energy Agency (IEA), 2016. *Key World Energy Trends: Excerpt from World energy balances*, 19p.

IUCN, U., 1980. World conservation strategy: Living resource conservation for sustainable development. Gland, Switzerland, International Union for the Conservation of Nature and Natural Resources (IUCN).

Kasturirangan, K., Aravamudan, R., Deekshatulu, B.L., Joseph, G. and Chandrasekhar, M.G., 1996. Indian Remote Sensing satellite IRS-1C – the beginning of a new era. *Current Science*, 70(7), pp. 495-500.

NRSC, 2012, Manual of National Land Use/Land Cover Mapping (Second Cycle) Using Multi-temporal Satellite Data. National Remote Sensing Centre, Department of Space, Hyderabad, pp. 1-11.

Pezzey, J. 1992. "Sustainable Development Concepts: An Economic Analysis". World Bank Environment Paper No. 2. Washington, D.C. 45p.

Ray, S.S., Crop Assessment using Space, Agro-Meteorology & Land-based observations: Indian Experience. *International Seminar on Approaches & Methodologies for Crop Monitoring & Production Forecasting*, 25-26 May, 2016, Dhaka.

Suhag, R., 2016. Overview of Ground Water in India. Accessed at http://www.prsindia.org/administrator/uploads/general/1455682937~~Overview%20of%20Ground%20Water%20in%20India.pdf

Vyas, S.S., Bhattacharya, B.K. and Nigam, R., 2016. Assured solar energy hot-spots over Indian landmass detected through remote sensing observations from Geostationary Meteorological Satellite. *Current Science*, 111(5), pp. 836-842.

WCED (World Commission on Environment and Development), 1987. *Our Common Future*. Oxford University Press: Oxford, 400p.

World Bank, 1987. Environment, Growth, and Development. *Development Committee Pamphlet 14*, World Bank, Washington DC.

World Bank, 2016. World Development Indicators 2016. Washington, DC: World Bank. doi:10.1596/978–1-4648–0683–4

Power Scaling Laws In Particle Physics and Astrophysics

Rudolf Muradyan

1. Introduction. What is Scaling?

Any power law

$$f(x) = cx^n$$

where exponent may be a positive or negative number, exhibits the property of *scaling* or scale *invariance*. The word scaling expresses the fact that function is $f(x)$ *shape-invariant* with respect to dilatation (resizing) transformation:

$$x \to \lambda x$$
$$f(\lambda x) \equiv c(\lambda x)^n = \lambda^n f(x)$$

The constant n is called degree of homogeniety, and the constant c has the dimension:

$$\dim c = \frac{\dim f}{(\dim x)^n}$$

Differentiating function $f(\lambda x)$ with respect to λ and putting $\lambda=1$ we obtain a simple differential equation for scaling function (Euler):

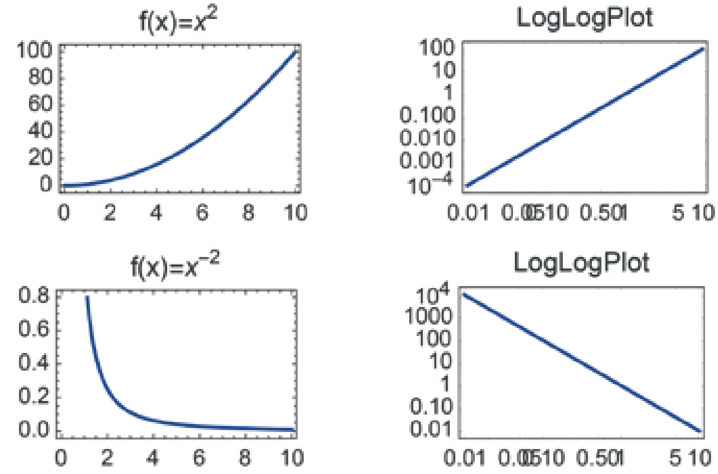
$$x\ f'(x) = n\ f(x)$$

There are tremendously many different scaling laws in Nature. A Google search on the Nobel prize official site nobelprize.org for scaling picks up nearly 100 results for "scaling".

Usually knowledge of scaling laws is enough to grasp essential characteristic of physical phenomena even without explicit knowledge of governing equations.

In revealing scaling properties a special role is played by the representation of data in double logarithmic or log-log plot. Any scaling curve $y=cx^n$ in x, y plane is possible to recast as straight line in X, Y plane, where $X=\log x$, $Y=\log y$. Any base can be used for logarithm.

The following is a simple example of scaling in log-log plane:



Now consider a homogenious function of two variales of degree n:

$$f(\lambda x, \lambda y) \equiv \lambda^n f(x,y)$$

By setting $\lambda = \frac{1}{x}$ we obtain an alternative equivalent expression for homogeneous function of two variables as product of a power function x^n times some function of one variable:

$$f(x,y) = x^n f\left(1, \frac{y}{x}\right) \equiv x^n \phi\left(\frac{y}{x}\right)$$

Actually all scaling relations are established on this ground. Generalization for many homogeneous variables is obvious.

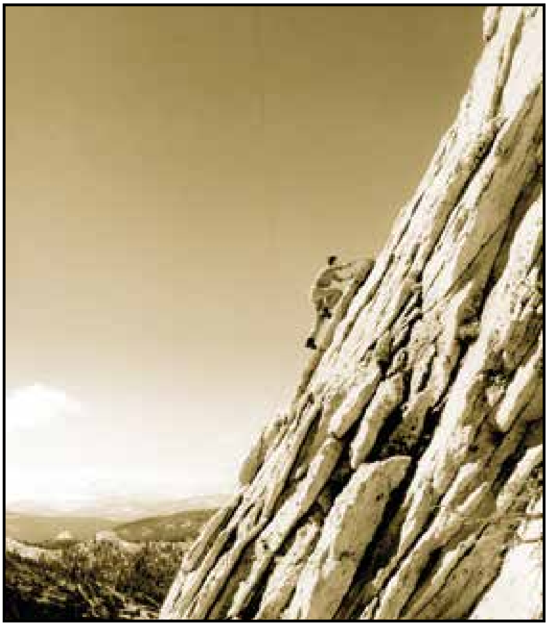
Let us note that any *dimensionless combination* of variables a,b,x,y, say $\left[\frac{a \cdot x^n}{b \cdot y^m}\right] = 1$ (or π-*group* according to Buckingham) defines some power scaling law $y = \frac{a}{b} x^{\alpha}$, where $\alpha = n/m$ [13].

2. Bjorken Scaling

In 1966, prior to SLAC scattering experiments, James "Bj" Bjorken predicted the scaling behaviour for structure functions of deep inelastic scattering (DIS) of electrons on nucleon. This surprising behaviour was found in the data of famous Stanford Linear Accelerator Center (SLAC) experiments and coined as "Bjorken scaling".

Establishment of Bjorken scaling was one of the most important discoveries in modern high energy physics. It was a direct manifestation of the existence *quarks* as fundamental constituents of hadrons. Bjorken scaling played a decisive role in the emergence and acceptance of Quantum Chromodynamics (QCD) modern theory of strong hadronic interactions. According to QCD, quarks are permanently bound inside hadrons and probably never will be observed as free particles. Nevertheless they really exist inside the hadrons. Quarks are fundamental particles in Gell-Mann&Zweig's *quark model*, proposed in 1964 and constitute the basic blocks of unitary simmetry. Bjorken evaded directly using the name "quark" during his analysis of data. In 1967 he even claimed: "... additional data are necessary and very welcome to destroy the picture of elementary constituents".

But later experiments persistently provided confirmation for quarks existence. Experiments at SLAC performed by H. Kendall, J. Friedman, and R. Taylor confirmed Bjorken's predictions on scaling and existence of hard point-like constituents inside the proton. Like Rutherford cracked the atom and discovered the proton, J. Bjorken, H. Kendall, J. Friedman, and R. Taylor cracked the proton and unveiled quarks.



James "Bj" Bjorken climbing Cathedral Peak in Yosemite National Park in 1960. (Courtesy of Henry Kendall).

James "Bj" Bjorken, SLAC theoretical physicist, at Hawaii Topical Conference, 1985.

3. Bjorken Scaling and Dimensional Reasoning (Matveev, Muradyan, Tavkhelidze & T. D. Lee)

Original derivation of Bjorken scaling was performed using current algebra and infinite momentum frame (Bjorken Limit) and was rather complex [1]. Bjorken made a great contribution for clarifying the nature of strong interactions. His radical scaling prediction obtained solid experimental confirmation.

But there is another approach based on plane dimensional analysis which leads to the same results.

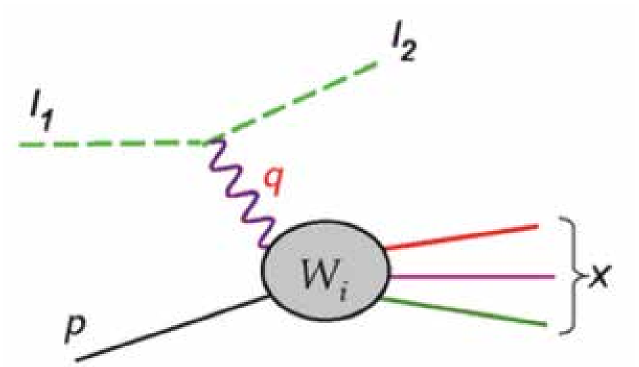
The reaction equation of inelastic scattering of electrons on nucleon can be written as

$$e+p\to e+X$$

where X is the unobserved hadronic system (usually pions), and called *missing mass*.

Kinematics of inelastic electron proton scattering is represented below.

If a single electron is detected in the final state then the cross-section is expressed in terms of two form factors (structure functions) $W_1(\nu,q^2)$ and $W_2(\nu,q^2)$ which depend upon two Lorentz-invariant variables: $\nu = pq = m(E-E')$ is proportional to the energy transfer from electron to hadrons, and $q^2 = -4EE'\sin^2\vartheta/2$ is the squared four-momentum transfer or the virtual photon mass.



Let us formulate the scaling (or automodelity) principle. We assume that in describing electromagnetic (or weak) interactions for large energies and momentum transfer none of the dimensional quantities, like masses, "elementary length" etc. are predominant and thus the structure functions depend only upon variable invariants. Therefore, when the scale of measurment of the momentum changes by a factor λ, the structure functions of deep inelastic electromagnetic and weak processes are expected to transform as homogeneous functions of appropriate dimensionality.

It is easy to calculate the dimensionality of the form factors

$$[W_1]=1,\ [W_2]=m^{-2}$$

Under scale transformation $p\to\lambda p,\ q\to\lambda q$ it follows that

$$W_1(\lambda^2 q^2,\lambda^2 v)=W_1(q^2,v),\quad W_2(\lambda^2 q^2,\lambda^2 v)=\lambda^{-2}W_2(q^2,v)$$

These conditions can be satisfied if we put

$$W_1(v,q^2)=F_1\left(\frac{v}{q^2}\right)$$

$$W_2(v,q^2)=\frac{1}{v}F_2\left(\frac{v}{q^2}\right)$$

Thus, although W_1 and νW_2 depend, generally speaking, upon two variables, at large q^2 and ν, according to automodelity or scaling principle, they may become functions of only one dimensionless variable. (In practice it is convenient to use the dimensionless variables ω or x defined according to $\omega=\frac{2v}{-q^2}=\frac{1}{x}$. Then in the physical region of electroproduction $1>\omega>\infty$ and $0>x>1$). Such behaviour of the structure functions of electoproduction had been predicted by Bjorken [1] on the basis of the connection of the structure functions W_1 and W_2 with almost equal-time commutators in the limit $q_0\to i\infty$ and $q_z\to\infty$. This prediction is in rather good agreement with the experimental data. Thus data for different q^2 and ν are described by single universal curve of nontrivial form.

Let us apply the scaling or automodelity principle to the simplest process $e^+e^-\to X$ of annihilation of an electron-positron pair to hadrons. The total cross-section of the reaction is described by a single spectral function $\rho(q^2)$ depending upon single variable q^2 being the square of the energy in the c. m. system:

$$\sigma_{tot}^{ee}(q^2)=\frac{8\pi^2\alpha^2}{q^2}\rho(q^2)$$

Since $\rho(q^2)$ is dimensionless, according to automodelity principle $\rho(\lambda^2 q^2)=\rho(q^2)=C$, where C is a constant. If this constant is not a zero then the annihilation cross section must behave asymptotically as $\sigma_{tot}^{ee}\sim\frac{const}{q^2}$ analogously to the "point" process $e^+e^-\to\mu^+\mu^-$. In the $x-$ space this prediction leads to vacuum expectation value of the electromagnetic current commutator being equal to

$$\langle 0|[J_\mu(x),J(0)]|0\rangle = \frac{iC}{\pi}(g_{\mu\nu}\Box-\partial_\mu\partial_\nu)\delta(\vec{x})\wp\left(\frac{1}{x_0}\right)$$

where $\wp$ is the symbol of the principal value. Hence it follows that the vacuum expectation value of the equal-time commutator between the time and space components $\langle 0|[J_0(\vec{x},0),J_i(0)]|0\rangle$ is equal to the Schwinger term with quadratically divergent c-number coefficient $\lim_{\tau\to 0}\frac{1}{\tau^2}\frac{iC}{\pi}\nabla_i\delta(\vec{x})$

It is necessary to note that the dimensional analysis method was independently proposed also by T.D. Lee for derivation of Bjorken scaling in electroproduction and other related processes. In his essay [2] he refers also to our approach. Below is an excerpt from T.D. Lee's essay.

Excerpt from T.D. Lee's essay

High Energy Electromagnetic and Weak Interaction Processes [2]
Physics Today, April 1972, p. 23
Scaling Hypothesis

"The scaling property is the consequence of the scaling hypothesis which was first suggested by Bjorken and others. All the consequences of the scaling hypothesis can then easily be derived by a pure and simple *dimensional analysis*. See also V.A. Matveev, R.M. Muradyan, and A.N. Tavkhelidze, JINR E2-5962, Dubna, 1971.

I wish to thank J.D. Bjorken for calling my attention to this preprint, in which the authors have also independently emphasized the importance of dimensional analysis in high energy physics".

V. Matveev, R. Muradyan, and A. Tavkhelidze at Bogoliubov Laboratory of Theoretical Physics (1973).

4. Lepton Pair Production in Strong Interactions (Matveev, Muradyan, Tavkhelidze & Drell-Yan)

The MMT&DY process is a deep inelastic electromagnetic effect when quark and antiquark from an colliding hadrons annihilate to create lepton-antilepton pair [3-6]:

$$a+b\rightarrow\mu^{+}+\mu^{-}+X$$

The quarkonium families of resonances J/ψ and Υ have been discovered during the study of dilepton spectra in this process.

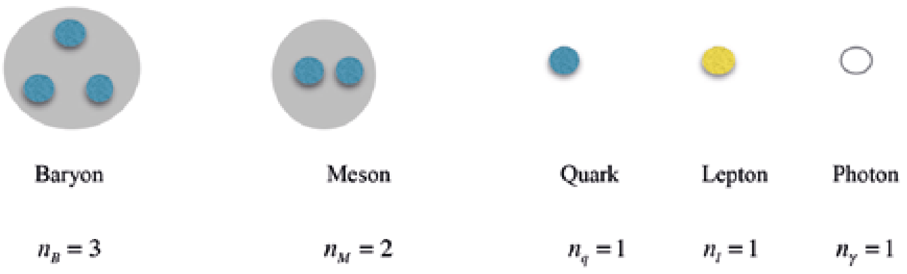
The tremendous potential of this process in understanding how quarks and gluons are confined inside a hadron, could be realized at the new accelerator collider complex NICA,[1] Dubna, Russia.

As noted the forefather of quark-gluon plasma research T.D. Lee:

> The NICA heavy ion collider will be a very major step towards the formation of a new phase of quark-gluon matter ... I am very much looking forward to the completion and future success of the NICA heavy ion collider.

5. Dimensional Quark Counting Rules (Matveev, Muradyan, Tavkhelidze & Brodsky-Farrar)

According to the quark model nonexotic barions and mesons consist of three quarks qqq and nonexotic mesons of quark-antiquark pair $q\bar{q}$. Quarks, leptons, and photons are pointlike.



In 1973 V. Matveev, R.M., and A. Tavkhelidze stated that asymptotic behaviour of inclusive 2→2 hadronic reactions contains information about distribution and dynamics of *quarks* in hadrons and proposed dimensional Quark Counting Rules (QCR) [7]. Concurrently dimensional QCR had been developed by Stanley Brodsky and his collaborators from SLAC.

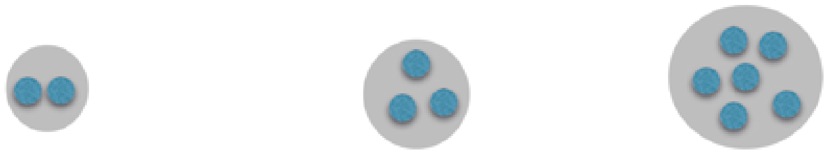
[1] NICA is abbreviation of Nuclotron-based Ion Collider fAcility.

QCR present straightforward conformation of validity of quark model and quark structure of hadrons. Investigation of scaling behaviour in exclusive 2→2 reactions is similar to analogous investigation of Bjorken scaling in DIS. Quark model was independently proposed by M. Gell-Mann and G. Zweig in 1964 on the basis of SU(3)-symmetry and generalization of the Sakata model. Sakata model was a precursor of the quark model and historically the SU(3) symmetry was first introduced in the Sakata model[2] in 1959.

Until discovery of Bjorken scaling in the SLAC DIS experiments the total opinion prevailed that quarks are auxiliary *mathematical devices* for description of SU(3)-symmetry. M. Gell-Mann and G. Zweig, creators of the quark model, initially were proponents of this point of view. QCR played a significant role in clarifying that quarks are real physical entities, not plane mathematical entities. In [7] a simple asymptotic behaviour for electromagnetic form factors was suggested. For composite object H with n_H constituents the corresponding form factor asymptotically must behave according to QCR:

$$F_H \sim \frac{1}{t^{n_H-1}}$$

where is corresponding Mandelstam variable. This relation shows that the more constituents has an object the faster is fall-off of the form factor.



$F_\pi(t) \simeq \frac{1}{t}$ $\quad$ $F_N(t) \simeq \frac{1}{t^2}$ $\quad$ $F_D(t) \simeq \frac{1}{t^5}$

Pion, $n_\pi = 2$ $\quad$ *Nucleon*, $n_N = 3$ $\quad$ *Deuteron*, $n_D = 6$

For two-body exclusive reaction Quark Counting Rules can be summarized as follows:

$$\frac{d\sigma^{ab\to cd}(s,t)}{dt} = \frac{1}{s^{n_a+n_b+n_c+n_d-2}} f\left(\frac{t}{s}\right) \quad or \quad \frac{d\sigma^{ab\to cd}(s,\vartheta)}{dt} = \frac{1}{s^{n_{tot}-2}} f(\cos\vartheta)$$

[2] Shoichi Sakata and his Kyoto group (M. Ikeda, S. Ogawa, Y. Ohnuki, Y. Yamaguchi, ...) were considered *Marxists* and marginalized by mainstream American physicists (as noted by David Kaizer, historian of science).

where $n_{tot} = n_a + n_b + n_c + n_d$ is the total number of quarks involved in the initial and final states of reaction, *s* and *t* are Mandelstam variables, *s* is square of the total energy in the center-of-mass frame, and *t* is the momentum transfer squared in the *s* channel; *f* is dimensionless function, depending on the details of the dynamics of the process and cos $\vartheta=1+2t/s$.

Some characteristic processes have following *s* dependence:

$$\frac{d\sigma^{ab\to cd}}{dt} \to \begin{cases} s^{-2} & ee \to ee, \quad \gamma e \to \gamma e \\ s^{-4} & e\pi \to e\pi \\ s^{-6} & ep \to ep, \quad \gamma p \to \gamma p \\ s^{-7} & \gamma p \to \pi p \\ s^{-8} & \pi p \to \pi p \\ s^{-10} & pp \to pp \\ s^{-11} & \gamma D \to np \\ s^{-12} & eD \to eD \end{cases}$$

Thousands of experimental works justify the validity of QCR predictions [8].

6. Huntley's Extension and Scaling in Inclusive Strong Interaction (Matveev, Muradyan, Tavkhelidze)

Huntley in his book (Huntley, H.E. (1967), *Dimensional Analysis*, Dover) pointed that sometimes it is useful instead of unoriented length dimension *L* to introduce directed dimensions $L = \{L_x, L_y, L_z\}$.

There are two striking empirical facts about the dynamics of the multi-hadron production in the collision of two hadrons at high energies:

6.1. Limited transverse momentum

One of the most surprising facts of multiparticle hadronic reactions at high energies is the limited range of the transverse momenta, i.e. the magnitude of the component of momentum in the perpendicular plane to the beam direction. The vast majority of the created particles have a restricted *transverse* momenta $q_T<0.4$ *Gev.* While with increasing collision energy *longitudinal* impulses of particles increase $q_z\to\infty$.

On a Peyrou plot of q_T *vs.* q_z with allowed kinematic domain radius $\sqrt{q_T^2 + q_z^2} \le \sqrt{s}/2$ almost all events cluster along the longitudinal z-axis in a strip $q_T<0.4$ *Gev.*

6.2. Slow particle number growth

The average number of particles $\bar{n}(s)$ grows slowly (logarithmically) with increasing energy. This means that most of the supplied energy is transformed into kinetic energy of longitudinal movement. In other words, interesting physics take place only in the longitudinal direction.

These two facts suggest that there is a strong dynamic difference between the longitudinal and transverse directions. That's why it is natural to introduce two different scales of length [9-10]:

L_z along the collision axis,

L_T in the transverse plane.

Any physical quantity F, measured in experiments on the collision of hadrons is characterized by certain dimensions in the longitudinal and transverse directions:

$$[F] = L_z^n L_T^m$$

Our main scaling hypothesis is the following:

At high energies, there are no fixed parameters having a longitudinal dimension. All basic constants such as the masses, effective radii, and other unknown parameters have purely transverse dimension.

Therefore, under scale transformations of the form

$$q_z \to \lambda q_z,\ \vec{q}_T \to \vec{q}_T$$

any physical quantity should vary as a homogeneous function of the corresponding longitudinal dimension:

$$F \to \lambda^{-n} F.$$

Let us now consider predictions of directed dimensional analysis for specific observables. The simplest inclusive process in two hadron interactions $p_1 + p_2 \to X$ is the measurement of total cross-section $\sigma_{tot}(s)$, where $s = (p_1 + p_2)^2 \approx 4p_z^2$. By definition, the total cross-section is characterized by a certain effective area perpendicular to the collision axis. Therefore, it is determined by the transverse dimension of length units as follows:

$$[\sigma_{tot}(s)] = L_T^2$$

The dimension of the invariant at high energies is purely longitudinal:

$$[s] = L_z^{-2}$$

Under longitudinal scale transformation according to our main hypothesis we have equality:

$$\sigma_{tot}(s) = \sigma_{tot}(\lambda^2 s)$$

from which it follows that σ_{tot} can not depend on s, that is

$$\sigma_{tot} = const$$

Of course logarithmic corrections cannot be captured by this simple method.

Now we consider the predictions of Huntley's extended dimensional analysis for the *differential* cross-section of elastic scattering. At high energies and fixed momentum transfers when $[t]=[\vec{q}_T^2]=L_T^{-2}$ the differential cross-section of elastic scattering has dimension

$$\left[\frac{d\sigma}{dt}\right]=L_T^4$$

and therefore, cannot depend on *s*, having a longitudinal dimension

$$\lim_{\substack{s\to\infty \\ t-fix}}\frac{d\sigma(s,t)}{dt}=f(t).$$

Total elastic cross-section $\sigma_{el}(s)$ and the slope of the diffraction peak $b(s)=\frac{d}{dt}\ln\frac{d\sigma}{dt}\Big|_{t=0}$ also are constant: $\sigma_{el}(s)=const,\ b(s)=const$.

One particle inclusive distribution $p_1+p_2\to q+X$.
In c.m. system four dimensional momenta have the following components at high energies

$$p_1=\{p_z,0,0,p_z\}$$
$$p_2=\{p_z,0,0,-p_z\}$$
$$q=\{q_0,\vec{q}_T,q_z\},\quad q_0=\sqrt{q_T^2+q_z^2}$$

The kinematics of an inclusive reaction $p_1+p_2\to q+X$ can be described by three Lorentz invariant variables

$$s=p_1p_2\approx 2p_z^2$$
$$s_1=p_1q\approx p_z(q_0-q_z)$$
$$s_2=p_2q\approx p_z(q_0+q_z)$$

Invariant differential cross-section can be represented as

$$d\sigma=\frac{d\vec{q}}{q_0}f(s,s_1,s_2)$$

Taking into account the dimensions of $[d\sigma]=L_T^2$ and $\left[\frac{d\vec{q}}{q_0}\right]=L_T^{-2}$ we can find dimension of function $[f]=L_T^4$. Invariant *s* always has longitudinal dimension $[s]=L_z^{-2}$ while s_1 and s_2 can have different dimensions in different phyisical situations. However their product always have definite dimension $[s_1s_2]=[p_z^2(q_0^2-q_z^2)]=[p_z^2q_T^2]=L_z^{-2}L_T^{-2}$.
Now let us consider three different asymptotic regions.

F_1 – Fragmentation of 1-st particle:

$$q_{z\to+\infty},\ s_1 \approx \frac{p_z q_T^2}{2q_z},\ s_2 \approx 2p_z q_z \quad \text{therefore}[s_1] = L_T^{-2},\ [s_2] = L_z^{-2}.$$

F_2 – Fragmentation of 2-nd particle:
This case follows from F_1 after replacing indexes
$1 \rightleftarrows 2$, $[s_1] = L_z^{-2}$, $[s_2] = L_T^{-2}$.

P – Pionization region. In this case $|q_z| \sim q_T$ and only product of s_1 and s_2 has definite dimension $[s_1 s_2] = L_z^{-2} L_T^{-2}$

In F_1 region under scale transformation $p_z \to \lambda p_z$, $q_z \to \lambda q_z$, $\vec{q}_T \to \vec{q}_T$ the equality $f(s,s_1,s_2) = f(\lambda s, s_1, \lambda s_2)$
can be fulfilled only if

$$f(s,s_1,s_2) \equiv f\left(\frac{s_2}{s}, s_1\right) = f\left(\frac{q_z}{p_z}, \vec{q}_T\right)$$

This result follows also from reggeization of $3 \to 3$ elastic amplitude $p_1 + p_2 + \bar{q} \to p_1 + p_2 + \bar{q}$ according to A. Mueller.

In pionization region from our main scaling hypotesis it follows:

$$f(s,s_1,s_2) \equiv f\left(\frac{s_1 s_2}{s}\right) = f(q_T)$$

in accordance with double regge expansion of $3 \rightleftarrows 3$ amplitude with trajectory $\alpha_P(0) = 1$.

C.N.Yang and coworkers (*Phys. Rev.* 188, 2159, 1969 and *Phys. Rev. Letters* 25, 1072,1970) underlined many of these results from the concept of *limiting fragmentation*. R. Feynman (*Phys. Rev. Letters* 23, 1415,1969) and A. Mueller (*Phys. Rev.* D2, 2963,1970) considered similar problems by different methods.

7. Spin/Mass Scaling for Celestial Bodies

There is geometry in the humming of the strings,
there is music in the spacing of the spheres (Pythagoras).

Georges Lemaître's Big Bang theory along with celebrated forecasts leaves several principal questions unanswered, including the rotation problem.

It is notable that two outstanding members of the Pontifical Academy of Sciences, Monsignor G. Lemaître and afterwards Sir Edmund Whittaker, considered the *Rotating Primeval Atom* as possible source of the origin of rotational motions in the Universe.

The central concept of our consideration is that *Rotating Primeval Atom* must be replaced by *Rotating Primeval Hadron* with generalized Regge like spin/mass relationship. It is amusing that after Chadwick's discovery of the neutron in 1932, Lemaître began to refer to that initial seed as *Neutronic Nucleus*. You can be sure that if he had lived in our times, instead of the rotating *Atom* or *Nucleus* he certanly would have preferred a primeval spinning *hadron*.

Most heavenly bodies, starting from asteroids, planets, and stars to galaxies and cluster of galaxies, possess rotational motion. The rotation of the Sun was observed by Galileo, who attributed the shift of the sunspots to it. Immanuel Kant was the first to suggest that the Milky Way rotates, and this was indeed confirmed by further obsevations.

In modern astrophysics rotation plays an important role in explaining the emission mechanism of pulsars, which are apparently neutron stars. It has been hypothesized that rapidly rotating dense objects lie at the centers of galaxies and quasars. Finally, indications have recently been found that the entire Universe as a whole may also rotate.

MONSIGNOR GEORGES LEMAÎTRE

"His view is interesting and important not because he is a Catholic priest, not because he is one of the leading mathematical physicists of our time, but because he is both".

Dunkan Aikman, journalist

SIR EDMUND TAYLOR WHITTAKER

"Rotation is a universal phenomenon; the Earth and all members of the solar system rotate on their axis, the satellites revolve round the planet, the planets revolve round the Sun, and the Sun itself is a member of a Galaxy or Milky Way system which revolves in a very remarkable way. How did all these rotary motions come into being? What secures their permanence or brings about their modification? And what part do they play in the system of the world?"

E. Whittaker

The central point of our consideration is that *Rotating Primeval Atom* must be replaced by *Rotating Primeval Hadron* with generalized Regge like spin/mass relationship. The fundamental spin/mass relation *à la* Regge for n-dimensional hadronic object has been proposed in our previous studies [11-13]:

$$J^{(n)}(m) = \hbar \left(\frac{m}{m_p} \right)^{\frac{1}{n}} \qquad n = 1,2,3$$

The number n=1,2,3 characterizes the geometric shape of hadron:

$$n = 1 \qquad \underset{(usual\ hadrons)}{string} \qquad J^{(1)}(m) = \hbar \left(\frac{m}{m_p} \right)^{2}$$

$$n = 2 \qquad \underset{(galaxies)}{disk} \qquad J^{(2)}(m) = \hbar \left(\frac{m}{m_p} \right)^{\frac{3}{2}}$$

$$n = 3 \qquad \underset{(stars)}{ball} \qquad J^{(3)}(m) = \hbar \left(\frac{m}{m_p} \right)^{\frac{4}{3}}$$

Kerr spinning black hole is completely characterized by two parameters: its mass m and spin J, connected by relation $J_{Kerr} = Gm^2 / c$. This relation establishes an upper bound on the maximum spin of a black hole.

It is remarkable that Kerr angular momentum can be obtained from the usual Regge formula for one-dimensional *string* like hadron by simple replacement of proton mass by Plank mass $m_p \to m_{Pl}$:

$$J_{Kerr}(m) = \lim_{m_p \to m_{Pl}} \hbar \left(\frac{m}{m_p} \right)^2 = \hbar \left(\frac{m}{m_{Pl}} \right)^2 \equiv \frac{Gm^2}{c}$$

where we have used identity:

$$\frac{\hbar}{m_{Pl}^2} \equiv \frac{G}{c}$$

For reader convenience let us recall the values of fundamental constants:

$$m_p = 1.673 \times 10^{-27} kg$$
$$\hbar = 1.055 \times 10^{-34} J \cdot s$$
$$c = 3 \times 10^8 m \cdot s^{-1}$$
$$G = 6.674 \times 10^{-11} m^3 \cdot kg^{-1} \cdot s^{-2}$$
$$m_{Pl} = \sqrt{\hbar c / G} = 2.177 \times 10^{-8} kg$$

In double logarithmic $\log_{10} - \log_{10}$ plot four straight lines represent the following functions:

$J^{(1)}(m),\ J^{(2)}(m),\ J^{(3)}(m),\ and\ J_{Kerr}(m)\ in\ SI-units,\ with\ [m]=kg\ and\ [J]=J\cdot s$

$$J^{(1)}(m)=3.769\times10^{19}m^2$$

$$J^{(2)}(m)=1.542\times10^{6}m^{3/2}$$

$$J^{(3)}(m)=53.11\ m^{4/3}$$

$$J_{Kerr}(m)=2.226\times10^{-19}m^2$$

Presently the situation with observational data for galaxies is very controversial. The *pre-dark matter* data are displayed in all $J-m$ plots. The observational data for planets and stars remain unchanged. For details see [11-13].

Kerr momentum plays an interesting theoretical role in our approach. It helps reveal important relations for limiting mass and spin of cosmic bodies as intersections with Regge trajectories $J^{(2)}(m)$ and $J^{(3)}(m)$. Thereby on the plane (m, J) we descovered two fundamental points with coordinates expressed simply by means of fundamental constants $\hbar, c, G, m_p$. We proposed to entitle this points as *Eddington and Chandrasekhar points*. Solving equation $\frac{Gm^2}{c}=\hbar\left(\frac{m}{m_p}\right)^{\frac{3}{2}}$ for variable m we obtain the Eddington expression for the mass of Universe and from the equation $\frac{Gm^2}{c}=\hbar\left(\frac{m}{m_p}\right)^{\frac{4}{3}}$ the celebrated Chandrasekhar expression for limiting mass of stars follows:

$$m_{Universe}=m_p\left(\frac{\hbar c}{Gm_p^2}\right)^2,\quad m_{star}=m_p\left(\frac{\hbar c}{Gm_p^2}\right)^{\frac{3}{2}}$$

Expressions for Eddington and Chandrasekhar masses via fundamental constants are considered jewels of theoretical physics and astrophysics. They concern fundamental properties of our Universe. Chandrasekhar's name was immortalized in connection with the formula for m_{star}. In his Nobel lecture he asks *"Why are the stars as they are?"* and responds because their masses are given by combination of fundamental constants given by formula for m_{star}.

Expressions for spins of stars and Universe J_{star} and $J_{Universe}$ are relatively *new* and can be obtained from our theoretical Regge formulas for $J^{(2)}(m)$ and $J^{(3)}(m)$ by simple substitutions $m\rightarrow m_{Universe}$ and $m\rightarrow m_{star}$. Corresponding relations for spins can be easily derived by this substitutions:

$$J_{Universe} = J^{(2)}(m_{Universe}) = \hbar\left(\frac{\hbar c}{Gm_p^2}\right)^3, \; J_{star} = J^{(3)}(m_{star}) = \hbar\left(\frac{\hbar c}{Gm_p^2}\right)^2.$$

It will be convenient here to summarize our main results, which can be represented in three different equivalent forms:

$Eddington\ po\text{int}\ \{m_{Universe}, J_{Universe}\}$	$Chandrasekhar\ po\text{int}\ \{m_{srar}, J_{star}\}$
$\left\{m_p\left(\frac{\hbar c}{Gm_p^2}\right)^2, \; \hbar\left(\frac{\hbar c}{Gm_p^2}\right)^3\right\}$	$\left\{m_p\left(\frac{\hbar c}{Gm_p^2}\right)^{\frac{3}{2}}, \; \hbar\left(\frac{\hbar c}{Gm_p^2}\right)^2\right\}$
$\left\{m_p\left(\frac{m_{Pl}}{m_p}\right)^4, \; \hbar\left(\frac{m_{Pl}}{m_p}\right)^6\right\}$	$\left\{m_p\left(\frac{m_{Pl}}{m_p}\right)^3, \; \hbar\left(\frac{m_{Pl}}{m_p}\right)^4\right\}$
$\left\{m_{Pl}\left(\frac{m_{Pl}}{m_p}\right)^3, \; J_{Pl}\left(\frac{m_{Pl}}{m_p}\right)^6\right\}$	$\left\{m_{Pl}\left(\frac{m_{Pl}}{m_p}\right)^2, \; J_{Pl}\left(\frac{m_{Pl}}{m_p}\right)^4\right\}$

The following identity can been used $\frac{m_{Pl}}{m_p} \equiv \sqrt{\frac{\hbar c}{Gm_p^2}}$ during transformation of these equations. Also it must be noted that $J_{Pl} = \hbar$ because of $J_{Pl} = m_{Pl}v_{Pl}r_{Pl} = \sqrt{\frac{\hbar c}{G}}c\sqrt{\frac{\hbar G}{c^3}} = \hbar$.

Let us consider the double logarithmic *J*,*m* plane. Any power function $y=cx^n$ in x,y plane can be recast as a straight line in X,Y plane, where X=log x, X=log y. In this log-log plot theoretical spin/mass relations represent straight lines.

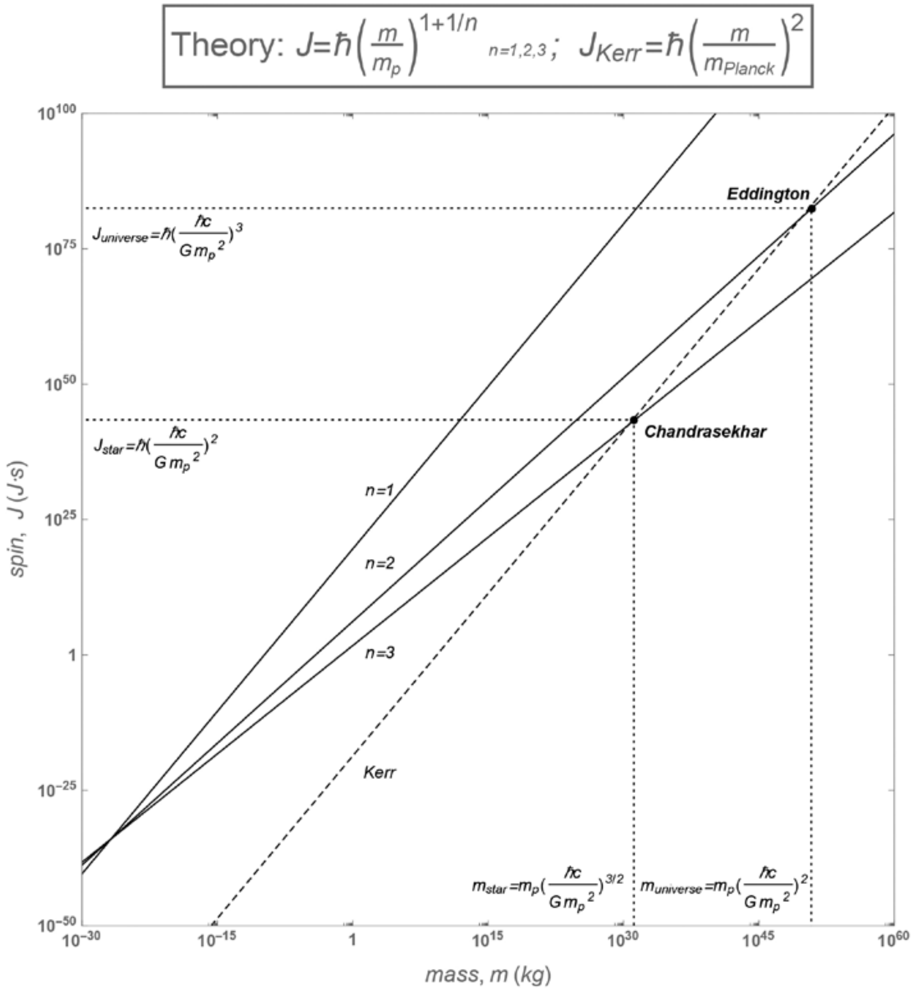


Figure 1. In double logarithmic plot $\log_{10} - \log_{10}$ three Regge spin/mass relations $J^{(1)}(m)$, $J^{(2)}(m)$, $J^{(3)}(m)$ and Kerr black hole spin/mass are presented. Kerr line is parallel to Regge trajectory $J^{(1)}(m)$ and intersects $J^{(2)}(m)$ and $J^{(3)}(m)$ in Eddington and Chandrasekhar points with indicated spin and mass coordinates.

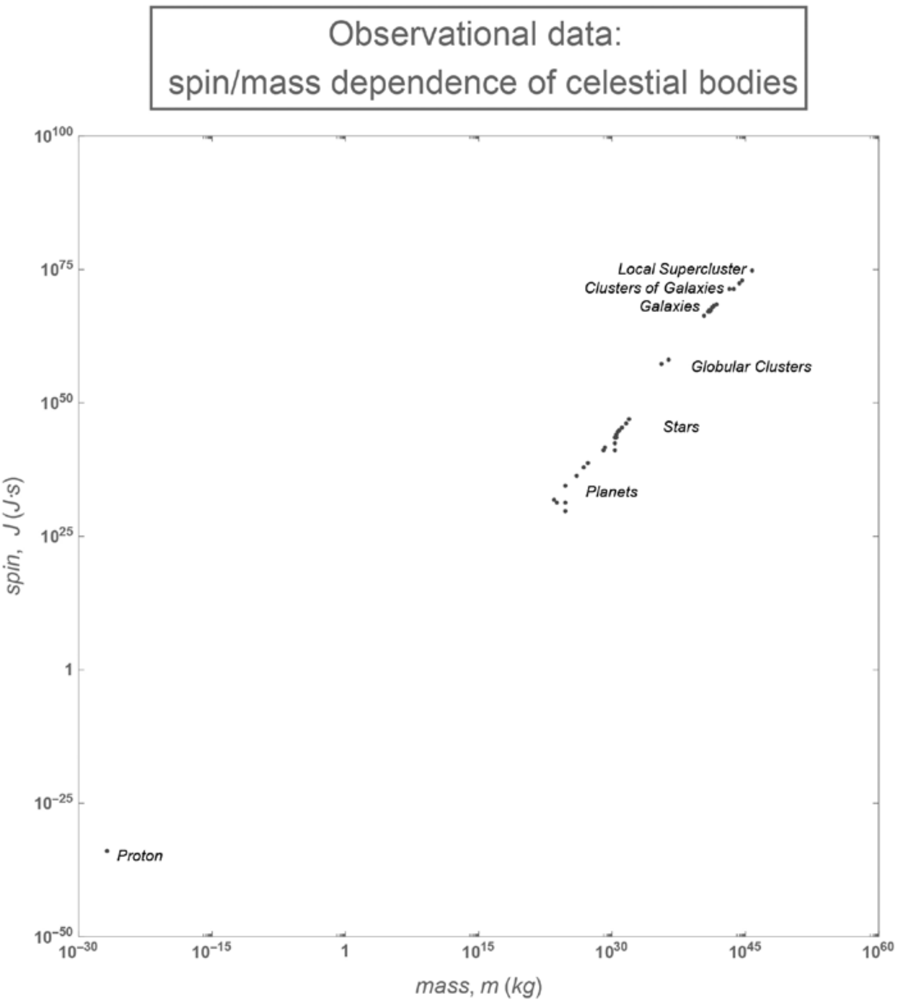


Figure 2. The observational data for planets and stars did not depend on presence or absence of dark matter. For galaxies and clusters of galaxies pre-dark-matter data are used from [11-13]. The *pre-dark matter* data for galaxies are displayed on our all J/m plots. Might there exist a hidden mass in galaxies? Apparently yes, but if this hidden mass participates in gravitational interactions, it could also possess a hidden Regge behaviour.

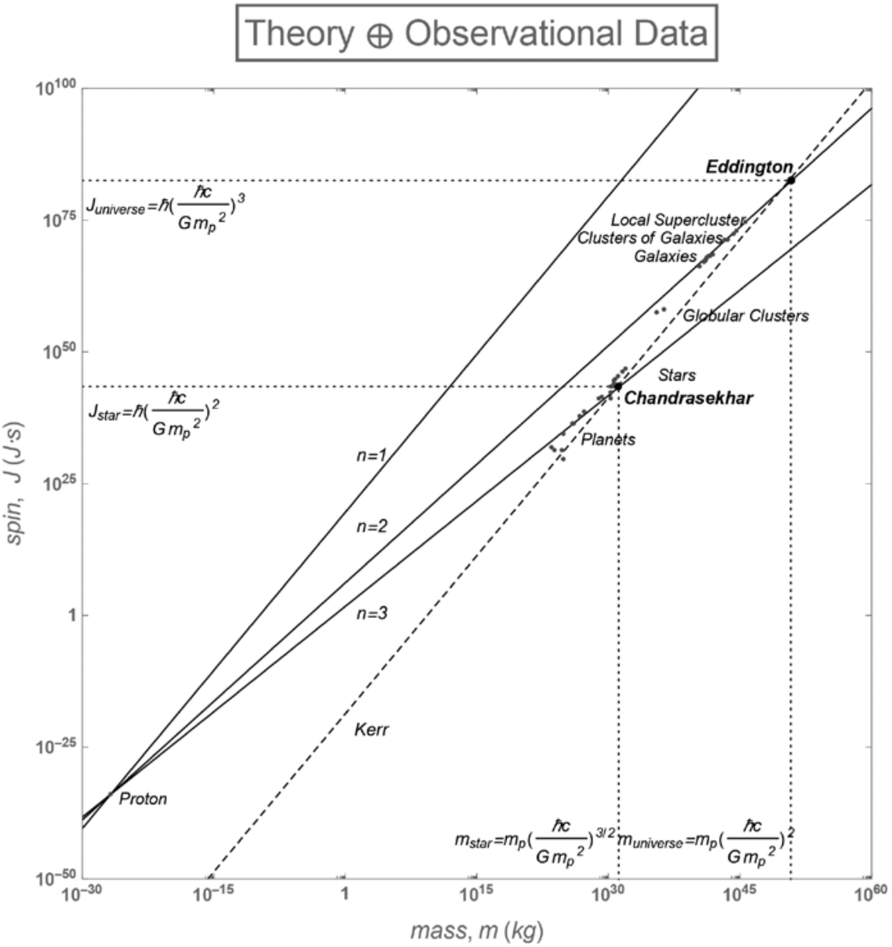


Figure 3. This plot represents superposition of Figures 1 and 2.

Let us consider some examples of numerical comparison of observational data with the theoretical predictions.

Jupiter

Jupiter is the fastest spinning planet in the Solar System. It takes 9.925 hours to complete one single rotation around its axis. The mass and spin of Jupiter are well known and are equal:

$$m_{Jupiter} = 1.90 \times 10^{27}\, kg$$

$$J_{Jupiter} = 4.32 \times 10^{38}\, J \cdot s$$

Theoretically calculated spin value neatly coincides with the observed one:

$$J_{Jupiter}^{theor} = \hbar \left(\frac{m_{Jupiter}}{m_p} \right)^{\frac{4}{3}} = 1.25 \times 10^{38}\, J \cdot s$$

Earth and Earth/Moon system

Earth is spinning, turning once on its axis every day, and completes one full turn on its axis during 23.93 hours. The observed mass and spin of the Earth are

$$m_{\oplus} = 5.97 \times 10^{24}\, kg$$

$$J_{\oplus} = 5.91 \times 10^{33}\, J \cdot s$$

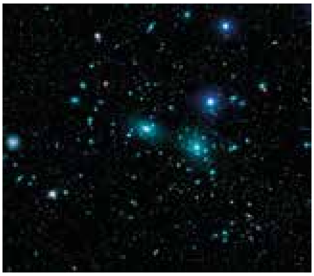
The theoretical prediction for Earth's spin

$$J_{\oplus}^{theor} = \hbar \left(\frac{m_{\oplus}}{m_p} \right)^{\frac{4}{3}} = 5.74 \times 10^{34}\, J \cdot s$$

is somewhat larger than the observed value, but closer to the observed total angular momentum of the Earth/Moon system

$$J_{\oplus + Moon}^{tot} = 3.47 \times 10^{34}\, J \cdot s$$

Coma Cluster (Abel 1656)



Every object in this photo is a galaxy. The Coma Cluster altogether contains 10,000 galaxies.

$$m_{Coma} = 2 \times 10^{14} m_{\odot}$$

$$J_{Coma} = 0.9 \times 10^{73} J \cdot s$$

The theoretical prediction gives a close number:

$$J_{Coma}^{theor} = \hbar \left(\frac{m_{Coma}}{m_p} \right)^{\frac{3}{2}} J \cdot s$$

Rotation of the Universe

Recently Michael Longo (U Michigan) analyzing data from Sloan Digital Sky Survey about thousands of spiral galaxies has shown that our Universe has a preferred axis and a net angular momentum. Because of angular momentum conservation this means that the Universe was born spinning. Earlier P. Birch (U Manchester) from the study of position angles and polarization of classical large radio-galaxies demonstrated the existence of a universal vorticity, that means that the Universe is rotating with an angular velocity. Using the numerical value of the spin of *Primeval Hadron,* one can estimate the rotational angular velocity of the Universe. It turns out that it coincides with Birch's result. The following estimate of the rotational angular velocity of the Universe seems realistic:

$$\omega_{Universe} = 10^{-3\pm1} \frac{radian}{age\ of\ Universe}$$

The rotation may play a role of repulsive force mimicking the role of effective or accelerating dark energy. Hence it can be considered as a substitute for dark energy, as noted by many researchers.

The expression for the angular momentum of the Universe

$$J_{Universe} = \hbar \left(\frac{\hbar c}{G m_p^2} \right)^{\frac{3}{2}}$$

has an interesting consequence

$$\frac{J_{Universe}}{r_{Universe}^3} = \frac{\hbar}{r_p^3} = \sigma$$

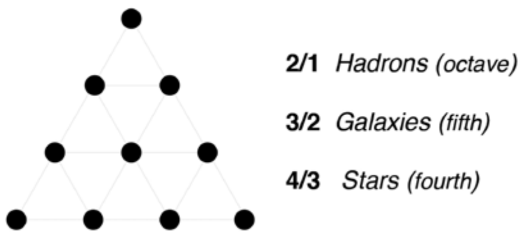
which mean that the spin density $\sigma \left([\sigma] = \frac{spin}{volume} \right)$ of the Universe is the same as for the proton. There is the notion that the spin density is the same for all structures, from elementary particles to galaxies and the Universe. The spin density in ECKS (Einstein-Cartan-Kibble-Siama) theory is related to the torsion Q by $Q = 4\pi G\sigma / c^3$ and, as it is well known, torsion acts opposite to gravity. Hence it represents a repulsive term and can be considered as candidate for dark energy.

It is obvious that the exponent in our main formula for spin mass relation $J^{(n)}(m) \simeq m^{1+1/n}$ $n = 1,2,3$ exactly coincides with Pythagorean perfect intervals *2* (*octave*), *3/2* (*perfect fifth*), *4/3* (*perfect fourth*), indeed

$$1 + \frac{1}{n} = \begin{cases} 2 & n = 1 \\ 3/2 & n = 2 \\ 4/3 & n = 3 \end{cases}$$

Is this amazing concidence a manifestation of *Modern Pythagorism*, indoctrinated by Max Planck and recently popularized by Frank Wilczek? Maybe. (F. Wilczek, Getting its From Bit, *Nature*, v. 397, 303-306, Jan 1999; http://ctp.lns.mit.edu/Wilczek_Nature/Getting%20Its%20from%20Bits.pdf).

Let us point out that *sacred* ratios 2, 3/2, 4/3 are encoded into *Tetractys* famous Pythagorean symbol



According to Pythagorean tradition the *Tetractys* is a rich transcendent symbol that embraces profoundly deep relationships. By some yet-unknown reason *Tetractys* encoded diverse physical phenomena. It symbolizes the fundamental numerical ratios that underlie the Universe.

We presented a new, quantum-mechanical model for the origin of the angular momentum of celestial bodies. Unlike the previous classical attempts, our approach gives surprisingly accurate numerical predictions of angular momentum for all spinning astrophysical objects. This occurs for the first time in the history of physics and astronomy. Another outcome from this approach is merely philosophical and witnesses the unity and simplicity of Nature in micro and macro scales.

Acknowledgements

The author wishes to express his gratitude to Victor Matveev and points out special appreciation for light years of invaluable collaboration. The substantial and generous email correspondence with James Bjorken is acknowledged, particularly for his inception of "Bjorken scaling" into physics.

References

1. J. Bjorken. *Phys. Rev.* 179 (1969) 1547; Asymptotic Sum Rules at Infinite Momentum, SLAC-PUB-510 (TH), http://inspirehep.net/record/52694/files/slac-pub-0510.pdf
2. T.D. Lee. High Energy Electromagnetic and Weak Interactions Processes, https://www.osti.gov/scitech/servlets/purl/4629305; A New High Energy Scale? *Physics Today*, April, 1972, p. 23
3. V. Matveev. Deep Inelastic Lepton-Hadron Interactions at High Energy, http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/05/138/5138698.pdf
4. R. Muradyan. Some Theoretical Problems of Deep Inelstic Lepton-Hadron Interactions, ICHP 70. http://cds.cern.ch/record/866855/files/C70-08-26-p658.pdf
5. V. Matveev, R. Muradyan, A. Tavkhelidze. Muon Pair Production in Strong Interactions and the Asymptotic Sum Rules, http://slac.stanford.edu/pubs/slactrans/trans01/slac-trans-0098.pdf
6. R. Kogerler and R. Muradyan. Joint Institute for Nuclear Research Report No. E2-4791, 1969.
7. V. Matveev, R. Muradyan, A. Tavkhelidze. Automodellism in the Large-angle Elastic Scattering and Structure of Hadrons, *Lett. Nuovo Cim.* 7(15); p. 719-723, 1973
8. INSPIRE. http://inspirehep.net/record/80967/citations
9. V. Matveev, R. Muradyan, A. Tavkhelidze. Scaling in Strong Interactions, http://www.mathnet.ru/links/3a98350b27a29fd028af0994aae29dbc/tmf3673.pdf
10. V. Matveev, R. Muradyan, A. Tavkhelidze. Automodelity in Strong Interactions, *Lett. Nuovo Cim.* 5, 907, 1972
11. R. Muradyan. Phys. The Regge Law for Heavenly Bodies, Part. Nucl., 28(5), 471-482, September-October 1997, American Institute of Physics.
12. R. Muradyan. Predictions in Astrophysics and Cosmology, http://www.pas.va/content/dam/accademia/pdf/acta19/acta19-muradian.pdf
13. R. Muradyan. Going from Quarks to Galaxies, http://www.casinapioiv.va/content/dam/accademia/pdf/acta18/acta18-muradian.pdf
14. R. Muradyan, A. Urintsev. DIANA: A Mathematica Code for Making Dimensional Analysis, Joint Institute for Nuclear Research Report No. E2-94-110, 1994.

Appendix

Gmail

rotation

Bjorken, James Daniel Thu, Feb 27, 2014 at 5:22 PM
To: rudolfmm@gmail.com

Dear Rudolf,

I just finished a read of your 1997 paper on rotation. It was total pleasure- - -so clearly written and so interesting. I entered the read with many doubts and questions on my mind. But by the end of the reading most everything had been addressed. A few comments:

At the biggest Big Picture level, your piece is a reminder that rotation is usually an essential complication, not an inessential complication. Since I started learning about gravity and cosmology post-retirement, I have for the most part set rotation aside. (But not completely- - -ten years ago I learned about Kerr black holes and thought quite a bit about them.) You make a very good case that an attitude that dismisses the importance of rotation may be very dangerous.

FRW inflationary cosmology- - -especially its initial conditition- - -also sets rotation aside. What is your attitude in this regard? At what point do you join the standard description? (exept of course for the rotation of your giant Prime-aval Hadron?) I have tried to construct my own answer to this question. First of all, dark energy (deSitter space) does not easily talk to rotation. So this suggets that rotation originated post-reheating. The epoch when CP violation entered the scene seems a natural place to introduce it. Then, once in the evolution, the question for me is where in the cosmic mix it is to be located. For me it is most likely to be localized at late times (after matter-radiation equality) in the visible-matter sector, which is the sector which talks to QCD- - -especially to its CP violation. A big problem of course will be to describe in detail the scenario that unfolds after the density contrast becomes of order unity and the cosmic web is created. But things are easier to anticipate in our long-term future. After several efoldings of dark-energy-driven reinflation, there will be islands of matter surrounded by a ocean of dark energy. This islands will have to contain the rotation you describe in Section 6. Trying to visualize the situation may be easier theoretically than dealing with the cosmic-web phenomenology itself.

In the 1990's I was part of a Fermilab experiment. A valued colleague on that effort was Mike Longo (U Michigan).

Since his retirement he got interested in looking for the mean helicity of spiral galaxies, and for a while clamed an effect at the 1% level (arXiv

1104.2815). He is very astute and careful experimentalist. I saw him last fall, and he has moved to other things- - -I got the impression that he of course got criticism and at the end of all that was left with an inconclusive result. But your equation 46 suggests that he got to an intrinsically interesting level. and if things could be pushed further out in sensitivity it might be worth another try. Have you looked at this kind of thing? If so, what are your opinion?

Finally, back at the Big Picture level, you remind me that non-rotating Schwarzschild black hole that all theorists (including me) love to death is more extremal than the extremal Kerr black hole. And there is an essential difference in terms of describing the singularity. Andrew Hamilton (U Colorado) is a colleague I have gotten to know in the last few years. He argues forcefully that the presence of an inner horizon makes a huge difference in the description of the insides of a realistic black hole. And I have my own little problem with the Schwarzshild limit, which can be described by the following simple homework problem:

Question: Consider a non-rotating black hole with a mass of order a galactic mass. Drop something in. It falls through the horizon toward the singularity. Assume it is destroyed by tidal forces when thouse forces become Planckian in scale. This death defines a spacetime event A. Do the same thing a year later; this describes another event B. The interval between A and B is spacelike. What is the distance between A and B? Answer: something like 10^33 cm.

This to me is surprisingly big. But if the geodesic part can somehow be thought of as “helical” the answer might be more intuitive.

Anyway, this reply is getting on the long side. But if nothing else, it is evidence that I really did enjoy your piece.

Regards,

bj

CHEMISTRY SESSION

Climate Change and Sustainability

Mario J. Molina

There is overwhelming scientific evidence behind the statement pointing out that human activities have already caused significant global warming. More than ten thousand peer-reviewed climate change articles have been published in the last couple of decades; less than one percent of these articles deny the warming is occurring, or that it is caused by humans. The Earth's climate is a complex system, and consequently projections of the average surface temperature increase in the future are uncertain; nevertheless, scientific research continues to demonstrate that there is a significant probability that this increase could reach five or more degrees Celsius towards the end of the Century if the release of greenhouse gases, coming mostly from burning fossil fuels, is not substantially limited in the near future. A change in climate of that magnitude would most likely have catastrophic consequences for human civilization.

The climate of our planet

Basic science has established quite clearly how the Earth's climate functions. Even if climate has experienced significant transformations in the past, these usually took place during tens of thousands of years, and were caused by factors such as massive volcanic eruptions, or periodic changes in the geometric parameters of the Earth's orbit, such as its ellipticity or the inclination of the Earth's rotation axis. It turns out that the climate has been exceptionally stable during the last twelve thousand years – the so-called "Eocene" geological epoch, thus enabling the development of human civilization. In contrast, climate variables such as the average surface temperature and the distribution and intensity of precipitation have changed substantially in recent decades, giving rise to what is known as "climate change".

The sun is practically the one and only source of energy for our planet. This energy arrives in the form of electromagnetic radiation, predominantly as visible light. Approximately one third of this energy is reflected back to space by clouds, deserts and snow, and the rest is absorbed by the oceans and by land. Since the Earth attained thermal equilibrium millions of years ago, it emits back to space the same amount of energy as it receives from the sun, mainly in the form of infrared or "thermal" radiation. During the 19th Century it had already been established experimentally what is known as the "black-body radiation law", that connects emitted radiation with temperature; according to this law, in the absence of the atmosphere the average surface temperature of our planet should be about -18° Celsius. The actual temperature is, however, closer to +15° Celsius, a value that has enabled the evolution of life as we know it; the reason is that the atmosphere functions as a blanket, increasing the average surface temperature by about 33° Celsius.

Thus, it turns out that the atmosphere plays a vital role establishing the actual surface temperature. About 99% of the atmosphere is made of nitrogen and oxygen, and the rest is mostly argon, an inert gas. These gases are transparent to visible radiation, thus permitting energy from the sun to reach the Earth's surface. They are also transparent to infrared radiation, and hence if only nitrogen, oxygen and argon were to be present in the atmosphere, it would not function as a blanket; however, it contains small amounts of certain gases that do absorb infrared radiation, which are the ones responsible for raising the surface temperature by 33° Celsius. These are the so-called "greenhouse" gases (GHGs): they include water vapor, whose concentration varies greatly, but is about 0.25%, on the average; carbon dioxide (about 0.04%), and other trace gases such as methane, and nitrous oxide, whose concentrations are measured in parts-per-million. Water vapor absorbs roughly three fourths of the infrared radiation emitted by the surface, and carbon dioxide most of the rest. The concentration of water vapor is highly variable, and depends crucially on the temperature; as a consequence, if carbon dioxide would somehow be removed from the atmosphere, the average temperature would clearly decrease, causing the water vapor to condense and eventually to return to the Earth's surface as liquid water, snow or ice, thus eliminating the "blanket" function of the atmosphere and decreasing the surface temperature by 33 or more degrees Celsius. For this reason, carbon dioxide is known as the "thermostat" of the planet.

Understanding climate change

During hundreds of thousands of years, the amounts of these gases in the atmosphere has remained relatively stable. However, since the beginning of the Industrial Revolution, in the late 19th Century, human society started to burn fossil fuels such as coal and oil, and the atmospheric concentration of carbon dioxide began to increase markedly, and has now reached more than 400 parts per million, a level that had not existed in several million years. In the same fashion, the atmospheric concentration of methane has more than doubled in recent years, also as a consequence of the activities of society. In other words, human activities have modified very significantly the composition of the atmosphere in terms of its greenhouse gases. The average surface temperature of the planet has increased by about one degree Celsius during the same time period, although the main change has taken place during the second half of the 20th Century. At first sight this change does not appear to be large, but it is very significant considering that the average temperature had decreased by only about 0.5° Celsius during the past eight thousand years. On portions of the planet, such as at high latitudes, the temperature change has reached as much as 3° Celsius; this explains why the amount of Arctic ice in the summer months has decreased enormously in recent years.

Because, as mentioned above, the Earth's climate is a complex system, scientists are cautions associating, for example, the observed chemical composition of the atmosphere with the observed temperature changes. Nevertheless, the Intergovernmental Panel on Climate Change (IPCC), a voluntary association of climate scientists, concluded in its fourth report, published in 2007, that the probability that human activities are responsible for the observed temperature change is 90%; in its most recent report, published in 2015, the same probability was estimated as 95%. In other words, it is possible that the temperature increase observed during the same time period as the change in composition of the atmosphere is a mere coincidence, but this conclusion is extremely unlikely.

Extreme events

The scientific community is investigating whether the recently observed changes in the characteristics of the climate, which are mainly rises in the intensity, duration, and frequency of events such as hurricanes, floods, droughts, and heat waves are connected in some way to human activities. In view of the fact that relatively few such studies had been carried out in the past, the community had maintained a very conservative attitude related to the connection between those so-called "extreme events" and human-induced climate change. The relevant question is not whether such events would have occurred or not in the absence of climate change, but rather whether their intensity has increased. Consider, for example, heat waves: a recent study, based merely on temperatures measured by satellite at middle and low latitudes indicates that the probability of occurrence of an extreme heat wave has increased tens of times in the last half century. Yet another study examined six extreme events, including droughts and floods; the conclusion was that the intensity of five of them was indeed increased by climate change. Even more recent studies conclude that the intensity of hurricanes is indeed being affected by climate change, while others conclude that the damage caused by many forest fires has also increased significantly.

It is, thus, possible to conclude that many worrisome consequences of climate change are already taking place, and one can anticipate that as the average surface temperature continues to increase extreme events will occur more frequently, with important consequences for the well-being of human society. One expects, for example, a reduction in the productivity of agriculture, placing global food security at risk. On a longer time-scale, increase in sea-level rise, which is already well documented at present, will pose large risks to the coastal population in many parts of the planet.

Is it possible to successfully address climate change?

It is possible to reduce the climate change risks mentioned above, but it represents a large challenge for society: it would be necessary to reduce the emission of GHGs very significantly. The goal is to limit the average surface temperature rise to two degrees Celsius, which is the result of an estimation of plausible limits to prevent dangerous interference with the climate resulting from human activities.

To achieve this goal, it would be necessary to reduce GHGs emissions more than 50% before the year 2050, requiring a multitude of measures. The most effective would be an international agreement to place a cost on the emission of GHGs, which would thrive a profound change in the generation and use of energy. Such a measure would also require to provide resources to developing countries so that they could impose the necessary measures, without affecting their economic development.

There is no simple means of achieving the desired goal in reducing emissions; energy efficiency measures are not sufficient by themselves, and it is necessary to develop economically feasible technologies to generate renewable energy. Fortunately, solar and wind sources have become affordable in recent years, thus enormously facilitating the desired outcomes. Among other measures, it will eventually be necessary to use electric vehicles and to greatly reduce the use of fossil-fuel vehicles.

Climate change and the economy

A key question is whether the desired changes will be economically feasible. The production patterns employed in most developed countries have followed the logic of minimizing production costs and maximizing income, transferring a portion of the costs to the environment, as is the case of emitting wastes to the atmosphere, rivers, lakes and oceans, or of using natural resources without taking into account their limits. As time elapses, such short-term savings imply a sizable increment in the production costs for future generations.

In general, a free economy is based in market forces, to the benefit of buyers and sellers. But, if there are failures in the market forces, there are costs that economic agents place on others that are only paid by future generations; these represent the so-called "externalities". One way to deal with them is to place regulations that limit the behavior that imposes costs on others, amounting to the "internalization" of such costs. We can consider emissions of carbon dioxide and other GHGs as externalities, which implies that society needs to implement policies to disincentive such emissions. Furthermore, it is important to educate society so that it develops the appropriate culture required to implement such measures. The governments of some countries, such as Sweden and Australia, have already imposed industrial tariffs on carbon dioxide emissions.

Costs of mitigation vs costs of inaction

As recently as five years ago, economists considered that measures to reduce GHG emissions by 50% by the year 2050 would cost approximately 1% or 2% of global GDP, and that the costs of not implementing such measures would be significantly larger. These conclusions were emphasized, for example, by the Stern Report, one of the most influential economic studies published so far, generated as a request from the U.K. Government by Sir Nicholas Stern, of the London School of Economics. More recently, the price of electricity generated with renewable resources such as solar and wind energy has dropped significantly, due to technological advances, so that from an economic perspective these energy sources now compete favorably with fossil-fuel generated energy. Even though the cost of electricity generated by coal-fired thermoelectric plants remain low, these plants are now rapidly becoming obsolete in view of their large damaging impact on air quality, as has been demonstrated in various countries, particularly in China.

In a recent paper Sir Nicholas Stern indicates how the price of inaction regarding mitigation of GHG emissions has been grossly underestimated by most economic models, and that the damage to future generations cannot be measured solely on economic terms; their quality of life is at stake.

Game of roulette

One way to explain the uncertainty of the impacts climate change might have in the future is to make an analogy with a game of roulette. The Joint Program for Climate Change of the Massachusetts Institute of Technology has illustrated the results of their calculations, carried out with very sophisticated models of the global climate and of the global economy, simulating two roulettes that indicate the probabilities of given temperature changes towards the end of the Century for two different scenarios: the first one assumes that there is no change in the current tendency to generate GHG emissions (the business-as-usual scenario), and the other considering that efficient measures are implemented to reduce such emissions, for example, by means of an international agreement. The most worrisome aspect of the simulation is that for the business-as-usual scenario there is a probability of more than one in five that the surface temperature will increase five or more degrees Celsius. Should that result materialize, the world as we know it would largely disappear. Sea levels would rise by at least 10-15 meters, perhaps slowly, but unavoidably, affecting large urban populations. Many regions in the Sub-Tropics would turn into inhabitable deserts, causing massive migrations; and massive extinction of biological species would adversely affect ecosystem services that human civilization depends on.

Conclusion

It is clear that the effects of climate change are already taking place. If society reacts urgently and decidedly, we are still on time to avoid unnecessary costs and potentially catastrophic consequences that would imperil economic development and would seriously damage ecological systems in our planet. A logical conclusion of all these findings is that society confronts a large threat, and thus it is very important to modify its activities to limit the interference with the Earth's climate. This amounts to carrying out a second Industrial Revolution.

A transition towards efficient energy generation systems with low GHG emissions requires new investments as well as the deployment of innovative large-scale technologies. This represents a window of opportunity in the frame of a new economic development era. The solution requires a compromise of all sectors of society: academia, governments, opinion leaders, local and multinational enterprises, and society at large. It is necessary for all nations to implement measures to reduce GHG emissions. It is essential for developing countries to participate as well; perhaps some of them will require financial assistance from the developed world. In any event, there are many so-called "win-win" measures that do not require assistance, many of which have important side benefits, such as the improvement of air quality.

It is clear that climate change is already affecting the entire population of our planet. Science alone does not tell society what to do; economic, social and political considerations need to be considered, and ultimately, we all have an ethical responsibility towards the progress of civilization. To continue with the business as usual scenario, that is, ignoring the required restrictions on GHG emissions, would be highly irresponsible towards future generations, as they should be able to enjoy a quality of life at least as good as the one we have at the present time.

Splitting of Water by Artificial Photosynthesis

Chintamani N.R. Rao and Mohd Monis Ayyub

The energy requirement of the growing humanity as well as increased industrialisation is causing an energy crisis in the world. To overcome this crisis, it is crucial for us to develop clean, low cost and renewable sources of energy. Mimicking the natural photosynthesis in the form of photocatalytic water splitting to generate hydrogen is a viable option. Hydrogen can be used as a clean fuel to solve the energy crisis. Photocatalytic splitting of water utilises the sunlight to split water into hydrogen and oxygen, and we examine important aspects of photocatalytic water splitting in this article.

1. Introduction

The rate of depletion of fossil fuels and the environmental concerns caused by them has made it mandatory for researchers to search for a clean, renewable and inexpensive form of energy. In this regard, an inexhaustible energy source available to humanity is solar energy reaching earth's surface. There have been several attempts to utilise solar energy in the form of solar cells [1], photocatalytic water splitting [2], CO_2 reduction [3] and so on. Photocatalytic water splitting is a promising approach to solve the energy crisis as it produces hydrogen. Hydrogen is a good fuel for future purposes as it is the cleanest source of energy producing only water on burning and with the highest energy density per unit weight. In nature, plants convert solar energy to chemical energy in the process of photosynthesis. To mimic the process in nature, we have to first understand the process of natural photosynthesis and arrive at a strategy to make suitable catalysts for the efficient photocatalytic splitting of water.

2. Natural and Artificial Photosynthesis

Photosynthesis in plants occurs at reaction centres which are transmembrane proteins. The two reaction centres, PSII and PSI, are used in series in the so-called Z-scheme (Fig. 1a)[4]. The reaction centres contain antenna pigments which capture high energy photons as excitons and then funnelling them to the reaction centres leading to charge separation [5]. PSII utilises the visible light to carry out four-electron oxidation of two water molecules to oxygen. PSII (or P680) absorbs a photon and transfers an electron to pheophytin forming P680$^+$. The electron is transferred to PSI along a chain of molecules in order to reduce charge recombination. P680$^+$ subsequently takes an electron from water, oxidising it to oxygen, in a reaction catalysed by a water oxidising centre which is a cubic Mn_4O_5Ca cluster (Fig. 1b)[6]. The H^+ formed as a by-product of this reaction is reduced in the PSI. PSI (or P700) absorbs light and transfers an electron to reduce the H^+ converting NADP$^+$ to NADPH and generating P700$^+$. The electron from PSII is taken up by P700$^+$ returning it to its resting state thereby completing one cycle of photosynthesis.

Following the processes in natural photosynthesis, similar systems can be designed to carry out the process in the laboratory. Artificial pho-

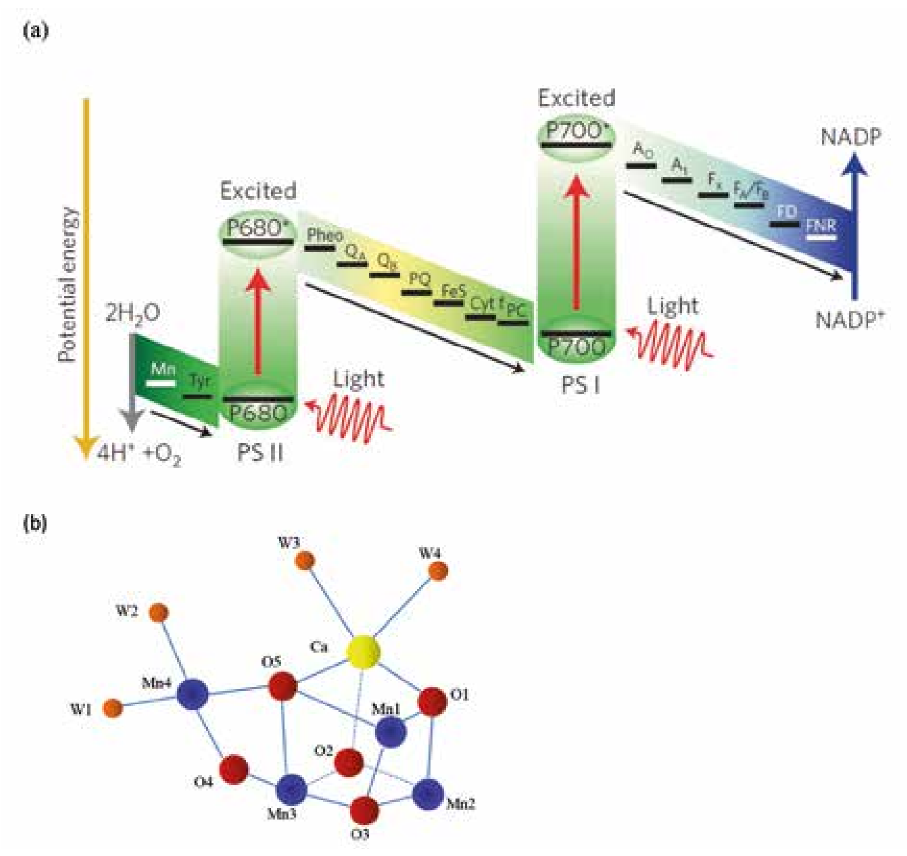


Figure 1. (a) Z-scheme charge separation process in a natural photosynthetic system (Reproduced from Tachibana et al.[4]) and (b) Structure of Mn_4O_5Ca WOC (Adapted from Umena *et al.* [6]).

tosynthesis consists of a light-harvesting unit, a catalytic centre and an electron-hole transfer pathway, suitably coupled with the two. It can be carried out in a single or a two-step process. The single step process involves a single photon absorber directly attached to an electron donor and an electron acceptor (Fig. 2a). The excitation site can be a dye molecule or a semiconductor. The absorption of light depends on the band gap of the semiconductor or the HOMO-LUMO gap of the dye molecule. The electron donor and electron acceptor should meet some principal requirements. The energy level of the electron donor must be more negative than the excited state reduction potential of the semiconductor or the dye and more positive than the water oxidation potential. Similarly, for the electron acceptor, its potential energy levels must be between those of the semiconductor or dye excited state oxidation potential and the reduction potential of water.

Analogous to the Z-scheme in natural photosynthesis the two-step process of artificial photosynthesis involves two-photon absorbers connected to each other by an electron-transfer relay material. It utilises two photons to generate one electron-hole pair. The two-step process can utilise lower energy sunlight, as low as infrared, to carry out the overall water splitting (Fig. 2b). The single-step process is simpler in comparison to the Z-scheme but has several drawbacks such as the choice of the chromophore is limited

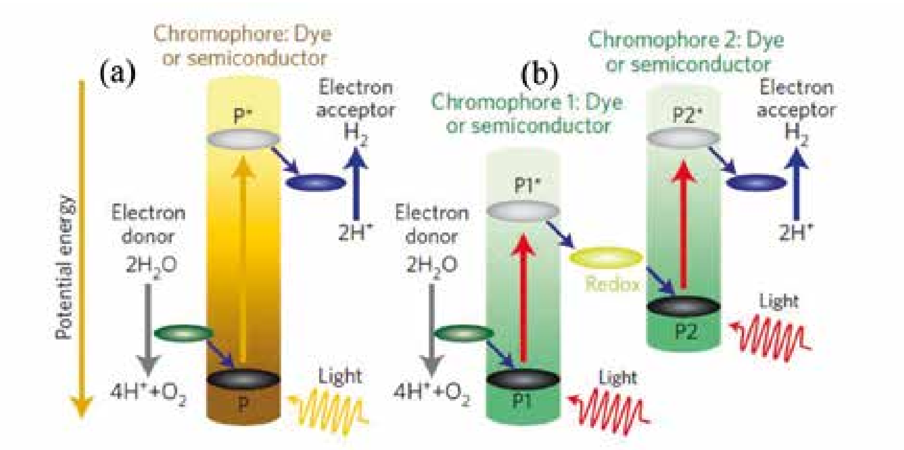


Figure 2. Artificial photosynthesis (a) one-step reaction and (b) two-step reaction (Reproduced from Tachibana *et al.*[4]).

due to the constraint on the potential energy of the excited state reduction and oxidation. Moreover, only a fraction of sunlight can be utilised in this process. The two-step process although utilising lower energy sunlight faces difficulty in maintaining the kinetics of the full electron-transfer process with minimal energy loss by charge carrier recombination.

3. Photocatalytic splitting of water

Several efforts have been made to mimic natural photosynthesis, involving splitting of water to produce hydrogen and oxygen via two redox reactions:

Reduction: $4H^{+}+4e^{-} \longrightarrow 2H_2$ (0V vs. SHE)

Oxidation: $2H_2O \longrightarrow 4H^{+}+O_2+4e^{-}$ (1.23V vs. SHE)

From the above chemical equations, it is evident that the water-splitting reaction requires a minimum of 1.23 eV, hence is an uphill process with a Gibbs free energy change of 237.2 kJ mol^{-1}. The oxidation half of the water splitting reaction has been shown to be the rate determining step in the overall reaction. In a study by Tang *et al.* it was shown that O_2 production takes ~1 s and the quantum yield peaks at 4 photons/particle [7, 8]. The first example of the overall splitting of water was reported by Fujishima

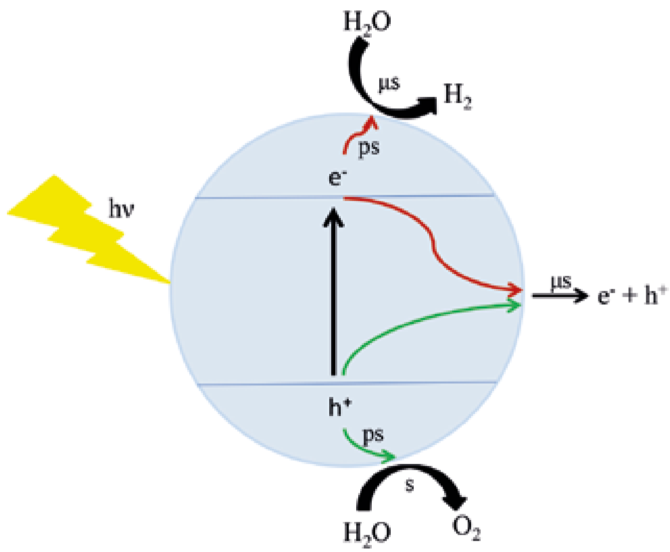


Figure 3. Mechanism of photocatalytic water splitting on a semiconductor (TiO2) and the timescale of various e^- - h^+ reactions (adapted from Moniz *et al.* [8]).

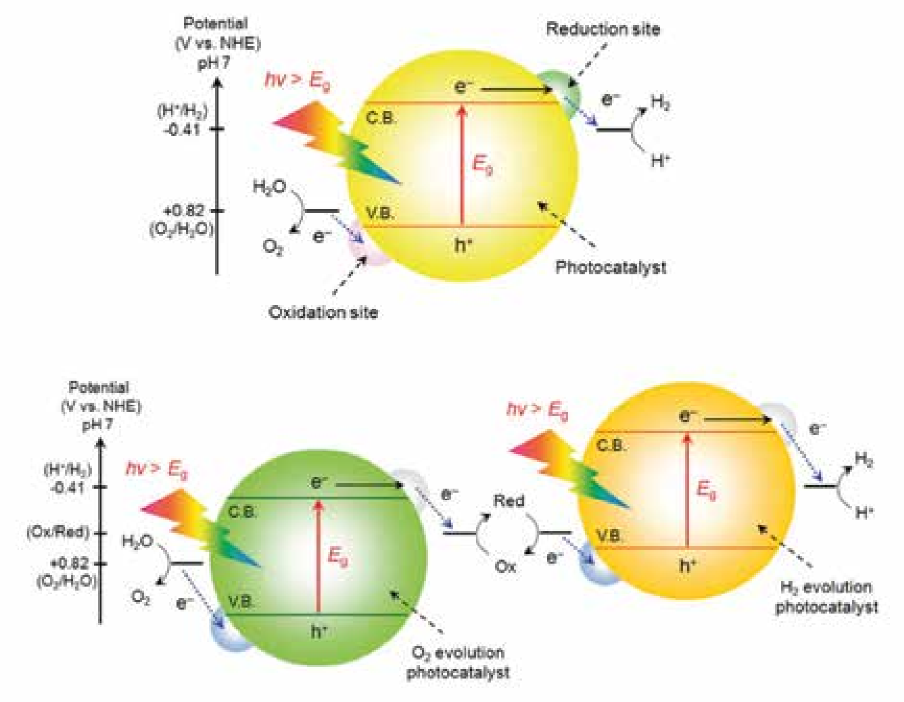


Figure 4. Schematic representation of (a) one-step and (b) two-step water splitting system (Reproduced from Maeda *et al.*[10]).

and Honda in 1972 with TiO_2 photoelectrodes under UV illumination [9]. The mechanism of natural or artificial photosynthesis broadly involves three aspects or steps: (i) absorption of light, (ii) generation and separation of charge carriers and (iii) redox reactions (Fig. 3).

Photocatalytic splitting of water can be carried out via two types of processes as mentioned above: one-step and a two-step process. The one-step process involves splitting of water into hydrogen and oxygen by a single photocatalyst. This photocatalyst must have thermodynamic potential suitable for water oxidation and reduction. The second approach, the two-step process, inspired by the natural Z-scheme uses two different photocatalysts (Fig. 4)[10].

The overall photocatalytic splitting of water employing a single photocatalyst is a challenging task, but one can preferentially carry out either water reduction (hydrogen evolution) or water oxidation (oxygen evolution) by the use of suitable sacrificial agents (electron or hole scavengers).

Splitting of water has been carried out by employing various types of catalysts broadly semiconductors based catalysts and dye-sensitised catalysts.

3.1 Semiconductor Catalysts

Semiconductors absorb photons of energy greater than its bandgap, generating an electron-hole pair. The electrons and holes subsequently migrate to the surface to carry out the redox reactions. Charge carrier recombination competes with the separation of charges and redox reactions. The position of the valence and conduction bands of the semiconductor determines the feasibility of the redox reactions.

After the excitation of the electron, the electron in the conduction band reduces the proton to hydrogen while the hole in the valence band oxidises water to oxygen. The potential of the electron and hole should be high enough to carry out the reduction and oxidation reactions, respectively. Thus, the conduction band minima must be more negative than the reduction of H^+/H_2 (0V vs SHE) and the valence band maxima must be more positive than the O_2/H_2O (1.23V vs SHE). This puts a theoretical limit on the minimum band gap of the semiconductor as 1.23 eV (Fig. 5). For a semiconductor to be a suitable catalyst for the splitting of water must fulfil this condition. Fig. 6 shows various semiconductors and their comparison with water reduction and oxidation potential.

Use of a sacrificial agent in the system provides a control over the products obtained. A hole scavenger, which is a strong reducing agent such as an alcohol or sulphide, gets oxidised by the hole in the VB (instead of water) suppressing the oxidation of water. Similarly, an electron scavenger

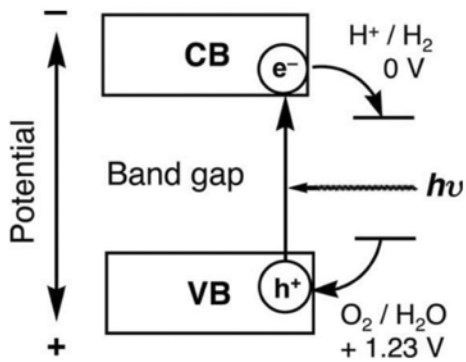


Figure 5. Potential of VB and CB with respect to the water reduction and oxidation potentials (Reproduced from Kudo et al.[15]).

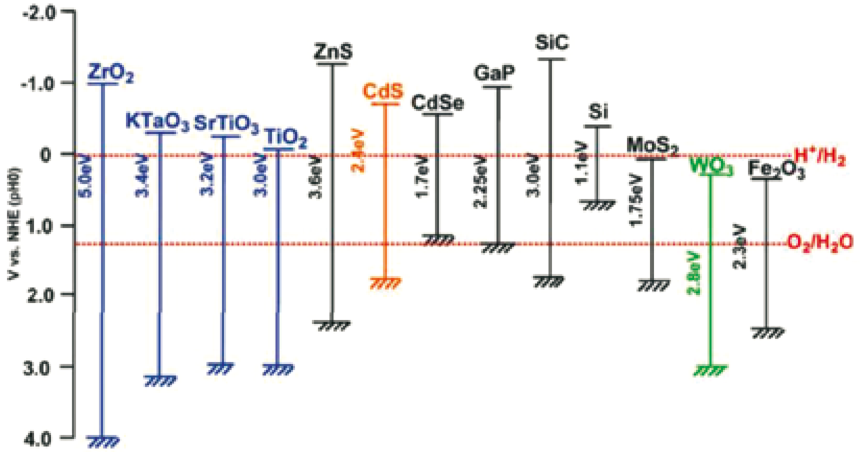


Figure 6. Comparison of band edge position of various semiconductors with the water reduction and oxidation potentials (Reproduced from Kudo et al.[15]).

gets reduced by the electron in the CB whereby suppressing the reduction of water. The use of a hole scavenger leads to only the hydrogen evolution reaction (HER) while the use of an electron scavenger leads only to the oxygen evolution reaction (OER).

3.2. Dye-sensitized Catalysis

Semiconductor photocatalysts suffer from the problem of a large band gap and inefficient utilisation of solar spectrum. These problems can be solved by sensitization of semiconductor with dyes, where it acts as a visible light responsive component. On absorbing a photon an excited electron is generated in the dye and if the excited state oxidation potential of the dye is more negative than the CB of the semiconductor, the electron is transferred to the CB of semiconductor, eventually causing a reduction a reaction [11, 12] (Fig. 7). The dye can be replenished by a sacrificial electron donor or redox shuttle such as $I3^{-3}/I^{-}$. A variety of materials in combination with dyes have been studied for the splitting of water [13, 14].

4. Reduction of Water

The simplest hydrogen evolution catalysts are semiconductor-based photocatalysts where the semiconductor acts as both the photon absorber and catalyst. Semiconductors such as CdS, CdSe, TaON, $Y_2Ta_2O_5N_2$, ZnO,

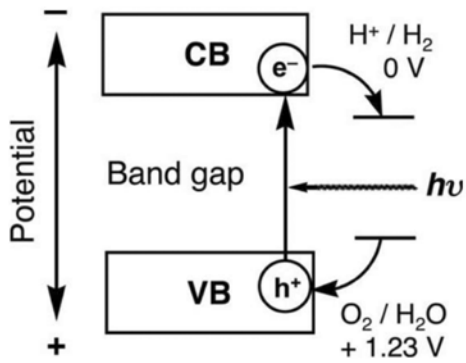


Figure 7. Schematic representation of dye-sensitised H_2 evolution (PS represents a photosensitizer) (Adapted from Maitra *et al.*[12]).

etc. have been studied extensively in this regard [15]. An ideal oxide semiconductor photocatalyst for the hydrogen evolution reaction (HER) must have a sufficiently negative conduction band for H_2 generation and a narrow band gap for visible light absorption, but it is difficult to develop such an oxide semiconductor. Few semiconductors possess the desirable VB and CB positions for overall water splitting and various means have been employed to synthesize the semiconductor photocatalysts with desirable features. Modification of the electronic structure by doping of cations and anions, for example, doping of nitrogen in large band gap semiconductors like TiO_2, ZnO decreases there band gap, making them photocatalytically active in the visible spectrum. Doping of oxides with only N induces defects and charge imbalance leading to recombination of charge carriers. Aliovalent anion substitution of F with N overcomes all these problems. Co-doping of N and F in ZnO has been shown to decrease the band gap considerably, rendering ZnO active in the visible spectrum and making it more active towards the reduction of water [16, 17].

Redox reactions of water splitting happen on a microsecond timescale whereas the charge carrier recombination occurs on a nanosecond timescale. This implies that most of the e^--h^+ pairs recombine before going to the surface for the redox reactions. Physical separation of water reduction and oxidation sites by using NiO-$NaTaO_3$ heterostructure has been demonstrated by Kato *et al.* [18] as an efficient method to overcome the fast charge carrier recombination. Various researchers have since explored various types of semiconductor heterostructures such as ZnO/CdS [19],

$TiO_2/SrTiO_3$ [20], etc. ZnO/CdS exhibit lifetimes up to 220 ns, whereas individual ZnO and CdS have a decay lifetime of only 60 ns [19]. A Pt-tipped CdS nanorod with embedded CdSe has been developed by Alivisatos and co-workers which has tunable properties [21]. Heterostructures of these types have a type II band alignment which ensures enhanced charge separation (Fig. 8). The charge separation and water splitting activity can be further enhanced by the use of co-catalyst such as RuO_2 and Pt which provides active sites for surface redox reactions.

Heterostructures of the type ZnO/Pt/CdS, $ZnO/Pt/Cd_{1-x}Zn_xS$ and $ZnO/Pt/CdS_{1-x}Se_x$ have been recently employed for water splitting under UV-visible and visible irradiation in our group (Fig. 8) [22]. It has been shown that by substitution of the anion and the cation in CdS modifies the optoelectronic properties of the ZnO/Pt/CdS heterostructures. A hydrogen evolution rate of 31.2 mmol h^{-1} g^{-1} with an apparent quantum yield (AQY) of 23.1% was obtained for $ZnO/Pt/Cd_{0.8}Zn_{0.2}S$ under UV visible irradiation in the presence of Na_2S-Na_2SO_3 as hole scavengers. This study was further extended by using doped ZnO in the heterostructures. Heterostructures of the type ZnO_{1-x} $(N, F)_x/Pt/CdS$ are indeed more active than the un-doped ZnO heterostructures exhibiting a hydrogen evolution rate of 43 mmol h^{-1} g^{-1} and AQY of 44% under visible light irradiation in the presence of benzyl alcohol-acetic acid as hole scavengers [23].

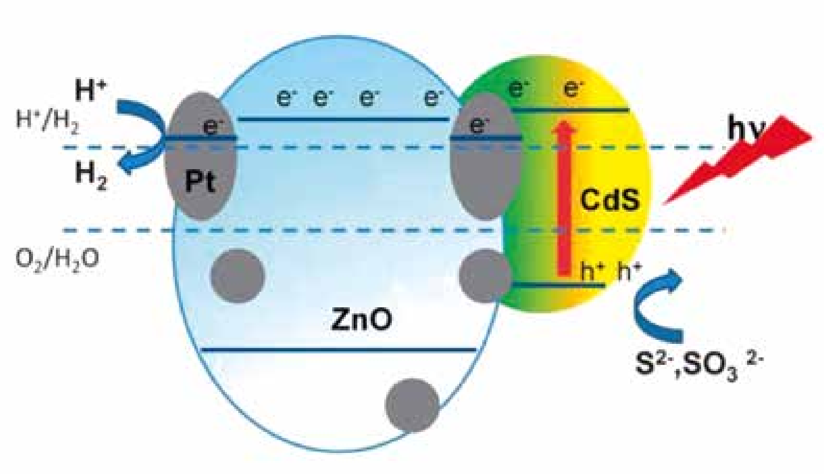


Figure 8. Schematic representation of the mechanism of charge separation and hydrogen evolution reaction under visible light irradiation on type-II heterostructures in the presence of Na_2S, Na_2SO_3 as sacrificial reagents (Reproduced from Lingampalli *et al.*[22]).

Another interesting hydrogen evolution catalyst is MoS_2, which is found to be useful both for electrochemical and photochemical hydrogen evolution reaction. The edge structure of MoS_2 bears a close resemblance to the active site of nitrogenase (hydrogen-producing enzyme), and it was shown theoretically as well experimentally that edges of MoS_2 are catalytically active, while the basal planes are inert [24, 25]. Bulk MoS_2 has an indirect band gap of 1.29 eV and on sensitisation with $[Ru(bpy)_3]^{2+}$ shows photocatalytic HER activity. MoS_2 crystallites supported on a conducting but otherwise inert substrate are good materials for HER. Enhanced HER has been reported for MoS_2 supported on grapheme [26] or carbon nanotubes [27]. A composite of MoS_2 with heavily nitrogenated RGO shows excellent HER activity, where incorporation of N in graphene enhances the electron donating ability of graphene. Single layers of the metallic 1T polytype of MoS2 was synthesized by Li intercalation followed by exfoliation which shows extraordinary HER activity of 30 mmol h-1 g-1 with a high turn-over frequency (TOF) of 6.25 h^{-1} [13]. It is to be noted that the electrons used in the reduction of water are not photocatalytically generated on MoS2 but transferred from the photosensitizer Eosin Y (EY). The

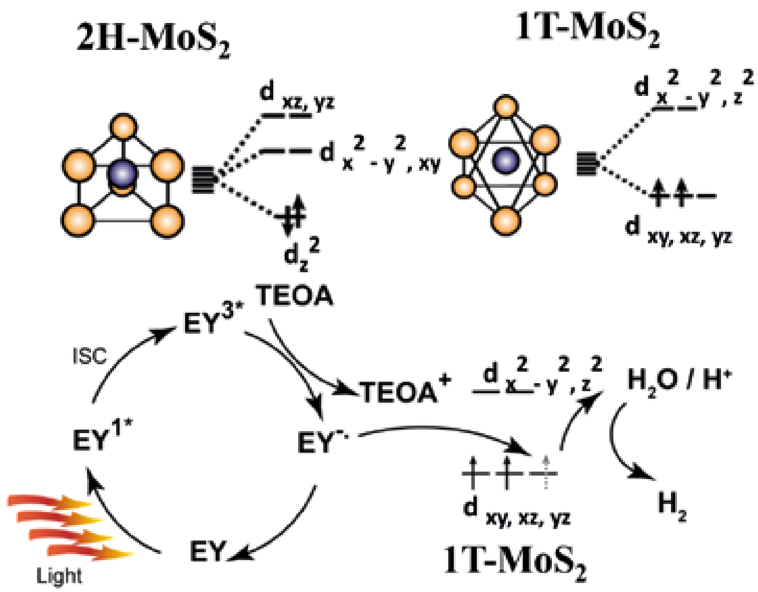


Figure 9. Schematic of dye-sensitized H_2 evolution over 1T-MoS_2 in the presence of Eosin Y (EY) and Triethanolamine (TEOA) (Reproduced from Maitra *et al.*[13]).

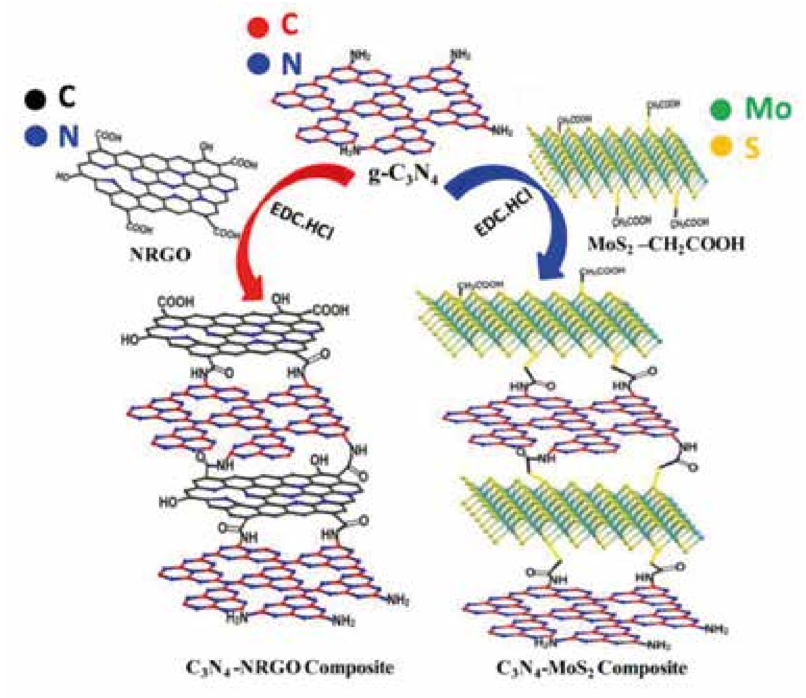


Figure 10. Synthetic strategy for covalently bonded C_3N_4-NRGO and C_3N_4-MoS_2 composites (Reproduced from Pramoda *et al.* [30]).

photosensitization of EY generates highly reductive species EY^- which subsequently donates an electron to MOS_2 [28] (Fig. 9). The 1T polytype of $MoSe_2$ is even more active than the 1T MoS_2 with a HER activity of 62 mmol h^{-1} g^{-1} and TOF of 15.5 h^{-1} [29]. A recent study from this laboratory shows a strategy to covalently cross-link C_3N_4 with sheets of MoS_2 as well as NRGO by carbodimide method. The study demonstrates beneficial effects of covalent bonding in C_3N_4-MoS_2 and C_3N_4-NRGO [30]. The cross-linked composites were shown to be more active than the C_3N_4 and MoS_2 separately. The enhanced HER activity is attributed to the increased planarity, enhanced charge transfer and higher surface area of the cross-linked composites (Fig. 10). DFT calculations show that the charge transfer occurs between cross-linked layers simultaneously through bonds as well as space [30]. The above phenomenon is also confirmed by MoS2-BCN composites which also show higher HER activity than the constituent compounds themselves.

5. Oxidation of Water

The oxygen evolution reaction (OER) which is an uphill reaction involving a four electron transfer process, is kinetically the key step in photocatalytic water splitting. RuO_2 and IrO_2 have been used widely as oxygen evolution catalysts [31-34]. The water oxidation catalyst in natural photosynthesis consists of cubane type Mn_4O_5Ca unit in PSII having $[Mn_4O_4]$ core. Similar to the WOC in natural photosynthesis, Mn and Co oxides with cubane-type units such as $[Mn_4O_4]$ and $[Co_4O_4]$[35-37], Marokite-type oxides, $CaMn_2O_4$ and $CaMn_2O_4.xH_2O$ have been shown as water oxidation catalysts [38, 39]. Nanoparticles of λ-MnO_2 obtained by delithiation of $LiMn_2O_4$ shows a much higher OER activity attributed to the extra flexibility of the [Mn4O4] cubic unit (Fig. 11) [40, 41]. Similarly, [Co4O4] cubic structural unit was demonstrated as the necessary criterion for catalytic activity of nanoparticles of $Li_2Co_2O_4$ [42]. A study from our group on Mn and Co oxides of spinel and perovskite structures shows that trivalency and the electronic configuration of the B-site metal cation is an important factor in determining OER activity. The cations with d4 and d6 configurations with a single electron in eg orbital show high activity

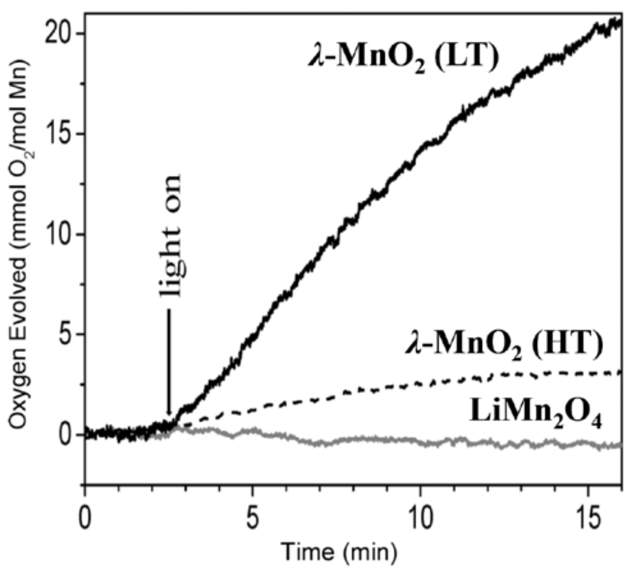


Figure 11. Oxygen evolution for λ-MnO_2 (LT), λ-MnO_2 (HT) and $LiMn_2O_4$ (Reproduced from Robinson *et al.* [40]).

irrespective of the crystal structure. Thus, Mn_2O_3, $LaMnO_3$ and $MgMn_2O_4$ with Mn in the +3 state with electronic configuration of t_{2g}^3 e_g^1 show good catalytic activity (Fig. 12). Similarly, compounds with Co^{3+} in the intermediate spin state (t_{2g}^5 e_g^1), such as $LaCoO_3$ and $Li_2Co_2O_4$ also show high catalytic activity. The singly occupied eg orbital yields the appropriate strength for the interaction between oxygen and the catalyst required for OER activity. The eg orbital forms σ-bonds with anion adsorbates and aids in the binding of oxygen-related intermediate species to the catalyst [43, 44].

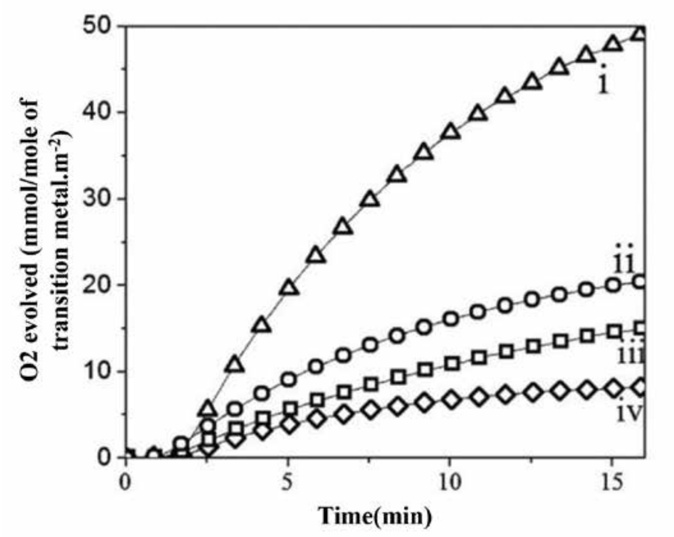


Figure 12. Oxygen evolution activity of different Mn and Co catalyst(Reproduced from Maitra *et al.* [43]).

6. Conclusions

There is need for concerted effort to solve the energy problem by discovering alternate sources. Water splitting to generate hydrogen using solar radiation is a viable option and there is considerable scope for innovation in this area. This article should serve to demonstrate the success and viability of photocatalytic splitting of water to produce hydrogen and oxygen, employing the strategy that nature adopts in photosynthesis.

References

[1] O'Regan, B. and Grätzel, M. (1991). A low-cost, high-efficiency solar cell based on dye- sensitized colloidal TiO2 films, *Nature*, 353, 737-740.

[2] Rao, C.N.R. and Lingampalli, S.R. (2016). Generation of Hydrogen by Visible Light-Induced Water Splitting with the Use of Semiconductors and Dyes, *Small*, 12, 16-23.

[3] Lingampalli, S., Ayyub, M. M. and Rao, C.N.R. (2017). Recent Progress in the Photocatalytic Reduction of Carbon Dioxide, ACS Omega, 2, 2740-2748.

[4] Tachibana, Y., Vayssieres, L. and Durrant, J. R. (2012). Artificial photosynthesis for solar water-splitting, *Nature Photonics*, 6, 511-518.

[5] McConnell, I., Li, G. and Brudvig, G. W. (2010). Energy conversion in natural and artificial photosynthesis, *Chemistry & biology*, 17, 434-447.

[6] Umena, Y., Kawakami, K., Shen, J.-R. and Kamiya, N. (2011). Crystal structure of oxygen-evolving photosystem II at a resolution of 1.9 Å, *Nature*, 473, 55-60.

[7] Tang, J., Durrant, J.R. and Klug, D.R. (2008). Mechanism of photocatalytic water splitting in TiO2. Reaction of water with photoholes, importance of charge carrier dynamics, and evidence for four-hole chemistry, *Journal of the American Chemical Society*, 130, 13885-13891.

[8] Moniz, S.J., Shevlin, S.A., Martin, D.J., Guo, Z.-X. and Tang, J. (2015). Visible-light driven heterojunction photocatalysts for water splitting–a critical review, *Energy & Environmental Science*, 8, 731-759.

[9] Fujishima, A. and Honda, K. (1972). Electrochemical photolysis of water at a semiconductor electrode, *Nature*, 238, 37-38.

[10] Maeda, K. and Domen, K. (2010). Photocatalytic water splitting: recent progress and future challenges, *The Journal of Physical Chemistry Letters*, 1, 2655-2661.

[11] Tributsch, H. and Calvin, M. (1971). Electrochemistry of Excited Molecules: Photo-Electrochemical Reactions of Chlorophylls, *Photochemistry and Photobiology*, 14, 95-112.

[12] Maitra, U., Lingampalli, S. and Rao, C.N.R. (2014). Artificial photosynthesis and the splitting of water to generate hydrogen, *Current Science*, 106, 518-527.

[13] Maitra, U., Gupta, U., De, M., Datta, R., Govindaraj, A. and Rao, C.N.R. (2013). Highly Effective Visible-Light-Induced H_2 Generation by Single-Layer 1T-MoS_2 and a Nanocomposite of Few-Layer 2H-MoS_2 with Heavily Nitrogenated Graphene, *Angewandte Chemie International Edition*, 52, 13057-13061.

[14] Gupta, U., Rao, B.G., Maitra, U., Prasad, B. and Rao, C.N.R. (2014). Visible-Light-Induced Generation of H2 by Nanocomposites of Few-Layer TiS2 and TaS2 with CdS Nanoparticles, *Chemistry – An Asian Journal*, 9, 1311-1315.

[15] Kudo, A. and Miseki, Y. (2009). Heterogeneous photocatalyst materials for water splitting, *Chemical Society Reviews*, 38, 253-278.

[16] Kumar, N., Maitra, U., Hegde, V.I., Waghmare, U.V., Sundaresan, A. and Rao, C.N.R. (2013). Synthesis, characterization, photocatalysis, and varied properties of TiO_2 cosubstituted with nitrogen and fluorine, *Inorganic chemistry*, 52, 10512-10519.

[17] Lingampalli, S.R., Manjunath, K., Shenoy, S., Waghmare, U.V. and Rao, C.N.R. (2016). Zn_2NF and Related Analogues of ZnO, *Journal of the American Chemical Society*, 138, 8228-8234.

[18] Kato, H., Asakura, K. and Kudo, A.

(2003). Highly efficient water splitting into H_2 and O_2 over lanthanum-doped $NaTaO_3$ photocatalysts with high crystallinity and surface nanostructure, *Journal of the American Chemical Society*, 125, 3082-3089.

[19] QingáLu, G. (2009). Enhanced photocatalytic hydrogen evolution by prolonging the lifetime of carriers in ZnO/CdS heterostructures, *Chemical Communications*, 3452-3454.

[20] Yang, Y., Lee, K., Kado, Y. and Schmuki, P. (2012). Nb-doping of $TiO_2/SrTiO_3$ nanotubular heterostructures for enhanced photocatalytic water splitting, *Electrochemistry Communications*, 17, 56-59.

[21] Amirav, L. and Alivisatos, A.P. (2010). Photocatalytic hydrogen production with tunable nanorod heterostructures, *The Journal of Physical Chemistry Letters*, 1, 1051-1054.

[22] Lingampalli, S., Gautam, U.K. and Rao, C.N.R. (2013). Highly efficient photocatalytic hydrogen generation by solution-processed ZnO/Pt/CdS, ZnO/Pt/Cd_{1-x} Zn_x S and ZnO/Pt/CdS_{1-x} Se_x hybrid nanostructures, *Energy & Environmental Science*, 6, 3589-3594.

[23] Lingampalli, S. and Rao, C.N.R. (2014). Remarkable improvement in visible-light induced hydrogen generation by ZnO/Pt/Cd_{1-y} Zn_y S heterostructures through substitution of N and F in ZnO, *Journal of Materials Chemistry A*, 2, 7702-7705.

[24] Jaramillo, T.F., Jørgensen, K.P., Bonde, J., Nielsen, J.H., Horch, S. and Chorkendorff, I. (2007). Identification of active edge sites for electrochemical H_2 evolution from MoS_2 nanocatalysts, *Science*, 317, 100-102.

[25] Hinnemann, B., Moses, P.G., Bonde, J., Jørgensen, K.P., Nielsen, J.H., Horch, S., Chorkendorff, I. and Nørskov, J.K. (2005). Biomimetic hydrogen evolution: MoS2 nanoparticles as catalyst for hydrogen evolution, *Journal of the American Chemical Society*, 127, 5308-5309.

[26] Li, Y., Wang, H., Xie, L., Liang, Y., Hong, G. and Dai, H. (2011). MoS2 nanoparticles grown on graphene: an advanced catalyst for the hydrogen evolution reaction, *Journal of the American Chemical Society*, 133, 7296-7299.

[27] Laursen, A.B., Kegnæs, S., Dahl, S. and Chorkendorff, I. (2012). Molybdenum sulphides – efficient and viable materials for electro-and photoelectrocatalytic hydrogen evolution, *Energy & Environmental Science*, 5, 5577-5591.

[28] Min, S. and Lu, G. (2012). Sites for high efficient photocatalytic hydrogen evolution on a limited-layered MoS2 cocatalyst confined on graphene sheets – the role of graphene, *The Journal of Physical Chemistry C*, 116, 25415-25424.

[29] Gupta, U., Naidu, B., Maitra, U., Singh, A., Shirodkar, S.N., Waghmare, U.V. and Rao, C.N.R. (2014). Characterization of few-layer 1T-MoSe2 and its superior performance in the visible-light induced hydrogen evolution reaction, *APL Materials*, 2, 092802.

[30] Pramoda, K., Gupta, U., Chhetri, M., Bandyopadhyay, A., Pati, S. K. and Rao, C.N.R. (2017). Nanocomposites of C_3N_4 with Layers of MoS_2 and Nitrogenated RGO, Obtained by Covalent Cross-Linking: Synthesis, Characterization, and HER Activity, *ACS Applied Materials & Interfaces*, 9, 10664-10672.

[31] Lee, Y., Ye, B.-U., Yu, H.K., Lee, J.-L., Kim, M.H. and Baik, J.M. (2011). Facile synthesis of single crystalline metallic RuO_2 nanowires and electromigration-induced transport properties, *The Journal of Physical Chemistry C*, 115, 4611-4615.

[32] Marshall, A. T. and Haverkamp, R.G. (2010). Electrocatalytic activity of

IrO_2–RuO_2 supported on Sb-doped SnO_2 nanoparticles, *Electrochimica Acta*, 55, 1978-1984.

[33] Lee, Y., Suntivich, J., May, K.J., Perry, E.E. and Shao-Horn, Y. (2012). Synthesis and activities of rutile IrO_2 and RuO_2 nanoparticles for oxygen evolution in acid and alkaline solutions, *The Journal of Physical Chemistry Letters*, 3, 399-404.

[34] Di Blasi, A., D'Urso, C., Baglio, V., Antonucci, V., Ornelas, R., Matteucci, F., Orozco, G., Beltran, D., Meas, Y. and Arriaga, L. (2009). Preparation and evaluation of RuO_2–IrO_2, IrO_2–Pt and IrO_2–Ta_2O_5 catalysts for the oxygen evolution reaction in an SPE electrolyzer, *Journal of Applied Electrochemistry*, 39, 191-196.

[35] McCool, N.S., Robinson, D.M., Sheats, J.E. and Dismukes, G.C. (2011). A Co4O4 "cubane" water oxidation catalyst inspired by photosynthesis, *Journal of the American Chemical Society*, 133, 11446-11449.

[36] Symes, M.D., Lutterman, D.A., Teets, T.S., Anderson, B.L., Breen, J.J. and Nocera, D.G. (2013). Photo-active Cobalt Cubane Model of an Oxygen-Evolving Catalyst, *ChemSusChem*, 6, 65-69.

[37] Brimblecombe, R., Koo, A., Dismukes, G.C., Swiegers, G.F. and Spiccia, L. (2010). Solar driven water oxidation by a bioinspired manganese molecular catalyst, *Journal of the American Chemical Society*, 132, 2892-2894.

[38] Najafpour, M. M., Ehrenberg, T., Wiechen, M. and Kurz, P. (2010). Calcium Manganese (III) Oxides ($CaMn_2O_4 \cdot x\ H_2O$) as Biomimetic Oxygen-Evolving Catalysts, *Angewandte Chemie International Edition*, 49, 2233-2237.

[39] Zaharieva, I., Najafpour, M. M., Wiechen, M., Haumann, M., Kurz, P. and Dau, H. (2011). Synthetic manganese–calcium oxides mimic the water-oxidizing complex of photosynthesis functionally and structurally, *Energy & Environmental Science*, 4, 2400-2408.

[40] Robinson, D.M., Go, Y.B., Greenblatt, M. and Dismukes, G.C. (2010). Water oxidation by λ-MnO_2: catalysis by the cubical Mn4O4 subcluster obtained by delithiation of spinel $LiMn_2O_4$, *Journal of the American Chemical Society*, 132, 11467-11469.

[41] Robinson, D.M., Go, Y.B., Mui, M., Gardner, G., Zhang, Z., Mastrogiovanni, D., Garfunkel, E., Li, J., Greenblatt, M. and Dismukes, G.C. (2013). Photochemical water oxidation by crystalline polymorphs of manganese oxides: structural requirements for catalysis, *Journal of the American Chemical Society*, 135, 3494-3501.

[42] Gardner, G.P., Go, Y.B., Robinson, D.M., Smith, P.F., Hadermann, J., Abakumov, A., Greenblatt, M. and Dismukes, G.C. (2012). Structural requirements in lithium cobalt oxides for the catalytic oxidation of water, *Angewandte Chemie International Edition*, 51, 1616-1619.

[43] Maitra, U., Naidu, B., Govindaraj, A. and Rao, C.N.R. (2013). Importance of trivalency and the eg1 configuration in the photocatalytic oxidation of water by Mn and Co oxides, *Proceedings of the National Academy of Sciences*, 110, 11704-11707.

[44] Naidu, B., Gupta, U., Maitra, U. and Rao, C.N.R. (2014). Visible light induced oxidation of water by rare earth manganites, cobaltites and related oxides, *Chemical Physics Letters*, 591, 277-281.

BIOLOGY SESSION

Sustainable Cohabitation of Living Organisms

Werner Arber

As a result of about 3.5 billion years of evolution of living organisms on our planet Earth, we can enjoy a large diversity of animals, plants and microorganisms. In many past scientific investigations, particular attention was paid to life processes of individual organisms. In recent times more and more attention is given to questions relating to an interdependence of different kinds of organisms living in the same habitat. Man and higher animals depend of course on finding their daily nutrition, mostly from food crops and animal products such as meat and milk. Since about 10,000 years, agriculture contributes essentially to this request.

In recent years, scientific investigations revealed highly relevant symbiotic cooperation between microorganisms and multicellular eukaryotic organisms including plants, animals and human beings. In these so-called microbiomes (1), the different partners help each other by providing particular essential functions. Think, for example, of the processes of food digestion.

Of high evolutionary relevance is the recently acquired knowledge on occasional events of horizontal (also known as lateral) gene transfer between different cohabitating organisms (2). Depending on the genetic function thereby acquired by the recipient organism, the latter can sometimes profit from an evolutionary development that had been made before by the donor organism. This process strongly depends on the same genetic language used by the donor and by the recipient organisms (3). This condition is fulfilled by the universality of the genetic code.

As we have previously outlined, horizontal gene transfer is one of the three natural strategies that contribute to the biological evolution (4). The other two natural strategies driving the process of biological evolution are, on the one hand, local nucleotide changes in the genome and, on the other hand, intragenomic rearrangement of DNA segments that can be duplicated, deleted, inversed or often translocated within the genome. The evolutionary usefulness of any novel mutant organism becomes tested by Darwinian natural selection. Many of these spontaneous mutagenesis events require a specific impact by enzyme activities (5) and sometimes also of nongenetic elements such as a structural instability of DNA parts displaying short-living isomeric forms (6).

These insights into the natural process of biological evolution had originally been obtained upon experimental investigations with microorganisms, but there is increasing evidence for their general validity for any kind of living organism. We can conclude that biological evolution does not result from accidents occurring to the genome; rather, biological evolution is actively driven by Mother Nature as a result of permanent creation by carefully securing a slowly ongoing biological evolution in the context of cosmic evolution, including terrestrial evolution of appropriate habitats for the living world.

By drawing his tree of evolution, Charles Darwin has symbolically shown that many present-day living organisms must have common roots. In view of the evolutionary strategy of DNA acquisition by horizontal gene transfer, we conclude that living organisms also have a common future (2). In this context, it is obvious that we have to avoid serious loss of biodiversity, which could drastically reduce future evolutionary developments of cohabiting organisms in their potential habitats. However, we are aware that some biodiversity components may occasionally become extinct. This can sometimes include a loss of a particular biological activity that could, at some future time, beneficially contribute to the human civilization. Measures to safeguard ("domesticate") such functions have recently been developed (7). Nevertheless, we should try to prevent by our lifestyle to actively contribute to extinguish other forms of life and thus, to reduce biodiversity on our planet. Only careful cohabitation with many other kinds of organisms can ensure long-term sustainable development of our civilization.

Scientific insights into the slowly ongoing cosmic evolution indicate that solar energy can still be provided to Earth for about three billion years, unless our planet suffers an unpredictable collision with a large celestial body.

Scientific conclusions on the slowly progressing evolutionary process can find full support by religious views that mankind is the crown of evolution on our planet and that we can act as shepherds of Creation. Thereby, we have the right to profit from the rich biodiversity encountered, but must carefully avoid any loss of biodiversity by our activities.

References

1. Blaser, M. Bork, P., Fraser, C., Knight, R. and Wang, J. (2013) The microbiome explored: recent insights and future challenges. *Nature, Rev. Microbiol.* 11, 213-217.
2. Arber, W. (1991): Elements in microbial evolution. *J. Mol. Evol.* 33, 4–12.
3. Arber, W. (2006): The evolutionary strategy of DNA acquisition is a possible reason for a universal genetic code. *Hist. Phil. Life Sci.* 28, 525-532.
4. Arber, W. (2007): Genetic variation and molecular evolution. In: *Genomics and Genetics*, Vol. 1, R.A. Meyers (Ed.) Wiley-VCH, Weinheim, pp.385-406.
5. Arber, W. (2005): Gene products with evolutionary functions. *Proteomics* 5, 2280-2284.
6. Watson, J.D. and Crick, F.H.C. (1953): The structure of DNA. *Cold Spring Harbor Symp. Quant. Biol.* 18, 123-131.
7. Rech, E.L. and Arber, W. (2013): Biodiversity as a source for synthetic domestication of useful specific traits. *Ann. Appl. Biol.* 162, 141-144.

New Developments in Genetic Engineering: Scientific and Ethical Aspects

Nicole M. Le Douarin

Technologies for manipulating DNA have enabled advances in biology ever since the discovery of the DNA double helix in 1953.

An important step in the process that led to modern molecular biology and genetic engineering took place in the 1970s, when researchers realized that they could *use bacterial enzymes*, which evolved to defend bacteria against pathogens, to modify DNA in other organisms.

Two technologies for manipulating DNA that have yielded very significant advances in this field have to be mentioned: the first one makes it possible to cut the DNA molecule at specific sites and relies upon the discovery of the *restriction enzymes* that are used by bacteria to defend against viruses and plasmids. These enzymes recognize definite base sequences in the DNA molecule and produce very specific cleavage fragments. They permitted the development of the *recombinant DNA technology* that transformed molecular biology and medicine. The discovery of restriction enzymes was acknowledged by the attribution of the Nobel Prize, in 1978, to Werner Arber, Hamilton Smith and Daniel Nathan.

Another remarkable progress in DNA technology was the *Polymerase Chain Reaction (PCR)*, a technique that allows the amplification of a single copy or a few copies of a piece of DNA across several orders of magnitude, generating thousands to millions of copies of a particular DNA sequence. This technique was made possible by the isolation of a DNA polymerase from bacteria *Thermus aquaticus,* living in hot springs, that retains its activity at high temperatures, designated as the Taq enzyme. This major technical advance was acknowledged by the Nobel Prize in Chemistry to Kary Mullis and Michael Smith in 1993.

But one technology consisting in introducing site-specific modifications in the genomes of cells and organisms remained elusive. However, two techniques were developed, based on the principles of DNA-protein recognition. One uses site-directed *zinc finger nucleases* (ZFNs) and the other, called TALEN, requires another type of nucleases, the "Transcription activator-like (TAL) effector nucleases". Difficulties of protein design, synthesis, and validation remained an obstacle to widespread adoption of these engineered nucleases for routine.

As David Baltimore said in his opening address at the International summit on *Human Gene Editing* that was held on December 1-3, 2015, at Washington, D.C., "*The methods available until recently were cumbersome and imperfect. Extending them to human beings was unthinkable. Over the years, however, the unthinkable has become conceivable*".

This was three years after the beginning of a new era. In 2012 a new tool made possible the editing of the genome of any type of living organism, including human, in a way that cumulates so many advantages when compared to the pre-existing techniques, that it has revolutionized the world of genome editing.

This new tool has generated great excitement in the scientific and medical community because of its potential to advance biological understanding, to alter the genome of microbes, plants, and animal and to treat human diseases. It is designated by the following acronym: *CRISPR/Cas9* or *Clustered, Regularly, Interspaced, Short, Palindromic Repeats* and *CRISPR associated protein 9*.

Its name is certainly known by most of the people in this audience, but I thought that the story of this discovery could be of interest, for the non-biologists essentially, but also for all of us, because of the ethical questions that are raised by this technology.

The CRISPR/Cas9 system was devised by the laboratories of two women scientists: one is a French bacteriologist, Emmanuelle Charpentier, who received her scientific education at the Pasteur Institute in Paris and was working in Sweden at the time of the publication of the technique in 2012, and the other is American, Jennifer Doudna, whose laboratory is at Berkeley University.

What is the origin of the CRISPR/Cas9 system?

Before the CRISPR/Cas9 System was engineered by Charpentier and Doudna, significant work had been carried out on bacteria that paved the way to this remarkable achievement. This system, like restriction enzymes and PCR, relies upon the means developed by the bacteria to defend against viruses.

The CRISPR/Cas9 system has two components, both derived from the bacteria *Streptococcus pyogenes*: Cas9, the endonuclease enzyme able to cause double strand breaks in DNA, since it possesses two catalytic sites, and a guide RNA (sgRNA) which guides Cas9 to the location in the genome of the targeted sequence. This second component of the CRISPR/Cas9 system (or sgRNA) has two parts: one (of 20 nucleotides) that recognizes (by Watson-Crick complementarity) the site where the breaks are to be created in the targeted DNA, and the other being linked to a CRISPR-RNA (designated crRNA) necessary to bind and stabilize the Cas9 protein.

These single guide RNA molecules can be produced with much less effort and expense than for all the other techniques used before for the same purpose. The CRISPR system has been discovered, in several steps, as an adaptive immunity mechanism in bacteria.

In 1987 the Japanese bacteriologist Atsuo Nakata discovered in the genome of *Escherichia coli (E.coli)*, short repetitive sequences of the four constitutive bases that characterize the oligonucleotides forming the double strands of the nucleic acid sequence (i.e. of DNA or RNA: Adenine -A, Thymine -T, Guanine -G, Cytosine -C – replaced by Uracyle in RNA).

These repetitive sequences are distributed in palindromes (a palindrome is formed a sequence followed by the same sequence in the inverse order) that can be read in both senses and produce hairpin structures. *Between these repeated structures, short strands of DNA* are *interspersed*. This discovery failed to arouse the interest of the scientific community at that time. In 2002, they were designated CRISPR, but their role was still unknown. In 2004 bioinformaticians discovered that the DNA intercalated between these palindromic repeats was often pieces of DNA belonging to viruses that infected the bacteria.

In 2007 researchers working for a Danish firm producing yogurts found that, among the bacteria (*Streptococus thermophiles*) that they used to produce the yogurts, those containing viral sequences in the CRISPR regions of their DNA were able to resist viral infection much better than the ones that did not.

This observation was interpreted as the capacity of the bacteria to capture pieces of viral DNA in their CRISPR system to use them during a second infection to kill the virus. In the same way as the immune system of vertebrates keeps memory cells from a primo infection to fight against the same germ a second time. *This is the principle of vaccination*. The Vertebrate immune system is endowed with *adaptive* immunity because it is capable of *adaptation,* a process that increases its efficiency in fighting against an invader.

The discovery of adaptive defence mechanisms in bacteria was in itself an important discovery because it showed that organisms as simple and apparently as rudimentary as prokaryotes have developed a sophisticated type of adaptive immunity. Moreover, it is this bacterial system that has been adapted to produce a tool that made it possible to edit the genome of all types of organisms.

Using the CRISPR/Cas9 system as a tool to edit the genome: a success story

In contrast to ZFNs and TALENs, which require substantial protein engineering for each DNA target site to be modified, the CRISPR-Cas9 system only requires a change in the guide RNA sequence. For this reason, technology using the *S. pyogenes* system has been rapidly and widely adopted by the scientific community to *target, edit, or modify* the genomes of a vast array of cells and organisms.

Variations have been devised in the use of the CRISPR/Cas9 system. For example, the Cas9 enzyme can be mutated, to break the scissors, so that it still binds DNA at the site that matched its guide RNA, but no longer slices it. Instead, the enzyme stalls there and blocks other proteins from transcribing that DNA into RNA. Thus the system is hacked and the gene is turned off, without altering the DNA sequence. By inventing a few other tweaks, researchers have built a way to turn genes on and off at will. By fusion of a fluorescent protein (such as green fluorescent protein) to the Cas9 enzyme, they can also produce live-cell imaging of chromosomal loci.

Many laboratories around the world have used CRISPR-Cas9 to edit genomes of a wide range of cell types and organisms. Thousands of articles have been published that include the CRISPR acronym in the title or abstract, since the beginning of 2013.

CRISPR-Cas9 has a large array of possible applications. It provides a robust technology for studying genomic rearrangements and the development and progression of cancers or other diseases. Other examples are the systematic analysis of gene functions in mammalian cells *and* the use of CRISPR-Cas9 for genome-wide studies that will enable large-scale screening for drug targets and thus will expand the nature and utility of genetic screens in human and other cell types and organisms. Another important CRISPR-Cas9 application with relevance to human health includes the ability to correct genetic mutations responsible for inherited disorders.

Ethical problems raised by the CRISPR/Cas9 system

In 2015 CRISPR/Cas9 was used in human pre-implantation embryos in China. The researchers used 86 tripronuclear zygotes (oocytes fertilized with two spermatozoa) that are not able to develop. The target gene was the b-globin gene that is mutated in b-thalassemia. They found that the endogenous gene was effectively cleaved (52%, 28 embryos) but many *off target events* were recorded and the embryos were mosaics with cells having different genomes. They found high rates of repair using endogenous sequences. These were obvious obstacles to gene therapy strategies using CRISPR/Cas9, since they could lead to unwanted mutations. This result showed that more work was required for using this system on human material and this first experiment was at the origin of serious ethical concern about the possible use of this technology in human reproduction.

In December 2015 scientists of major world academies called for a moratorium on inheritable human genome edits that would be passed on in pregnancies, including those related to CRISPR-Cas9 technologies, *but supported continued basic research and gene editing that would not affect future generations*. This position was further adopted by other Academies such as in England where British scientists were given permission by regulators to genetically modify human embryos by using CRISPR-Cas9 and related techniques, on condition that the embryos were destroyed in seven days. In the US the National Academies of Sciences, Engineering, and Medicine released a report on their "Recommendations for Responsible Conduct" of gene drives.

In genetics, "gene drive" means that the inheritance of a gene or a set of genes can be positively biased, even if it circumvents the Mendel traditional rules. In the case of a specific gene that normally has a 50-50 chance of being passed along the next generation, a gene drive, that can be achieved through CRISPR/Cas9, could push the rate to nearly 100%.

Several laboratories have shown that gene drive works in practice in the laboratory in fruit flies, mosquitos and yeast. Its application in the wild could be envisioned, for example, to fight malaria transmission. An anti-malaria gene drive might change a mosquito's genome so that the insect no longer had the ability to accept the malaria parasite, thus stopping the spread of the disease. A gene drive that forced all offspring to be male would make reproduction impossible, thus wiping out an entire population of a given species.

Opponents of the technique fear that permanently altering life forms on Earth will impact species and ecosystems in a way likely to be irreversible. As an example of the reactions raised by gene drive technology, I mention that the British primatologist Jane Goodall and dozens of other environmentalists and scientists have signed an open letter that calls for a halt to all proposals for the use of gene drive technologies "*given the obvious dangers of irretrievably releasing genocidal genes into the natural world*".

New Knowledge on the Causes of Human Birth Defects: Impact on Society

Edward M. De Robertis

Introduction

Two newly discovered causes of human birth defects will be discussed here. First, it has been found that *de novo* heterozygous mutations are a common cause of congenital heart disease, implicating hundreds of genes. Second, Zika virus presents us with a new epidemic that causes defects in fetal brain development by killing neuron progenitor cells in the cerebral cortex. The possibilities of new technologies for control of our ancient enemy *Aedes aegypti*, the mosquito vector of Zika, will be discussed. Finally, the consequences of these diseases for society and the dignity of the human person will be addressed.

Heart malformations caused by *de novo* loss of single genes

Congenital heart disease is the most frequent birth defect in humans affecting 0.8% of live births. Richard Lifton of Yale University invented the exome sequencing method by which one can readily sequence with the new high-throughput methods all human protein-coding regions, which are contained in less than 2% of our DNA. His team sequenced trios of hundreds of probands and their two parents. Unexpectedly, 10% of cardiac malformations had *de novo* loss-of-function point mutations that were deleterious to protein function causing premature termination, genetic code frameshifts, or splicing defects (1). These mutations were *de novo*, as they were absent from both parents. Since the patients were heterozygous, the mutations originated in the germ cells of one of the two parents.

While surgery can now repair heart defects very effectively, clinically some of these children fail to thrive presenting autism, slower growth and shorter life spans. By comparing the number of mutations detected only once to the number of genes mutated twice independently in the patients analyzed, the authors could calculate that an astounding 400 genes may be haploinsufficient for heart development in humans (1). Similarly, hundreds of potential heterozygous gene targets were found in children with autism (2, 3).

Some of the mutations were in histone methylation enzymes. Histones are proteins that form nucleosomes around which the DNA wraps around in order to be packaged and condensed. Histone-modifying enzymes cause epigenetic marks in every gene enhancer and promoter in the genome. Humans have at least 400,000 tissue-specific enhancers which are marked by a modification called H3K4Me (mono-methylation in Lysine 4 of Histone 3). Multiple mutated genes in this methylation pathway were identified (1). This means that specific phenotypes in heterozygous mutations can arise from very basic biochemical processes that affect every single cell in the body.

The basis of Mendelian genetics is that the loss of one gene (called an allele) is recessive and has no phenotype. These new findings imply that humans have hundreds, likely thousands, of genes that can cause disease if present in only one copy.

Microcephaly epidemic caused by Zika virus

Zika virus is an RNA virus of the Yellow fever family (called Flavivirus, for golden-yellow in Latin). Other members of this family include Dengue and Chikungunya viruses. Zika virus was first isolated from a sentinel monkey in the Zika forest in Uganda in 1947. In 2007 it infected humans in Micronesia, and in 2013 and 2014 epidemics took place in French Polynesia (4). In July 2015 an outbreak of the rare birth defect microcephaly appeared in the Brazilian Northeast, one of the poorest regions in the continent.

Zika virus infection presents itself with fever, skin rash, painful joints and muscles, conjunctivitis and sometimes blood in semen. The latter sign led to the early discovery that Zika virus can be transmitted sexually. With low frequency it can also induce Guillain-Barré syndrome, a paralysis caused by an autoimmune attack of peripheral nerves.

Zika virus causes microcephaly by infecting cerebral cortex neuron progenitor cells called radial glia and causing their death (5, 6). The human cortex adds neurons throughout embryonic development. One month after fertilization we have 10,000 brain cells, at two months 100,000, at 5 months 10,000,000, and at birth an estimated ten billion neurons. Additional cortical neurons are added during the first year. Consequently, infection at any time of pregnancy can produce grave defects. Most organ systems are formed between 4-8 weeks of embryonic development and teratogenic insults during the following fetal growth period produce relatively mild defects. The continuous birth of neurons in the cerebral cortex generates a uniquely prolonged target. Infection during late pregnancy may not cause microcephaly, but can still cause epilepsy and learning disabilities. Brain calcifications, a thin cerebral cortex, and enlarged brain ventricular cavities are radiologic signs of Zika virus viral infection.

Fighting our ancient enemy *Aedes aegypti*

Zika virus is transmitted by the Yellow fever mosquito *Aedes aegypti*. *Aedes*, which means odious in Greek, learned how to cohabit with humans 10,000 years ago in Africa by breeding in water storage containers inside dwellings (7). This species can be readily distinguished by the shape of a lyre on the back of its thorax. In Kenya, domestic and sylvatic (forest) *Aedes aegypti* mosquitoes coexist and interbreed in the same areas. By sequencing genes expressed in antennae, where their sense of smell resides, it was found that the key difference between both types of mosquitoes is the level of expression of an odorant receptor that senses a human odor called sulcatone (8). The domestic *Aedes aegypti,* but not the sylvatic form, strongly prefers biting humans rather than animals such as guinea pigs. The female of this mosquito has the odious habit of resting inside the shade of homes and biting multiple times per day. It usually bites during daytime, making bed nets ineffective. This behavior makes *Aedes aegypti* a very efficient vector to spread viruses from one human to another.

Aedes aegypti breeds near or inside homes in water barrels, flowerpots, plant pot bases, humid gutters, ditches, and discarded car tires and containers. The mosquito was imported into the Americas by the slave trade and even today redistributed by the transport of used car tires.

Substandard housing and lack of sanitation are a major problem in the underdeveloped world, explaining the sudden epidemic that has swept through Recife, Natal, Rio de Janeiro, Colombia, Venezuela, Puerto Rico and Cuba. During the Spanish-American war the US army lost more soldiers to Yellow fever than to fighting in Cuba. Dr. Walter Reed, serving as an officer, discovered that *Aedes aegypti* was the disease vector of a virus present in human serum after filtering through porcelain filters. Soldiers that consented to be bitten by infected mosquitoes died in this quest, but as a consequence of these studies most homes in the United States now have insect screens in their windows (and air conditioning in warm regions). Thus, diseases like Dengue fever that are very prevalent in poor countries of Latin America and the Caribbean have not affected the United States as much, despite the presence of *Aedes*.

In addition to sanitation, new mosquito control mechanisms are needed. Mosquitoes have killed more humans than any other animal if one includes malaria, which is transmitted by *Anopheles* (7). DDT use is now prohibited. Release of irradiated sterile males (or transgenic debilitated males) is not very effective because continued release in large numbers is required to decrease the population.

Wolbachia and CRISPR/Cas9 population-drive approaches

A very promising approach has been pioneered by Scott O'Neill of Melbourne, Australia, using *Wolbachia* bacteria. These intracellular bacteria infect 40% of all insects, but not mosquitoes. *Wolbachia* has spread through fruit flies of the genus *Drosophila* worldwide. *Wolbachia* is driven through insect populations by a phenomenon called cytoplasmic incompatibility. If an uninfected female mates with a *Wolbachia*-infected male, most of the resulting eggs become infected and die due to lack of immunity. However, once an infected female survives, she can mate productively with both infected and uninfected males. This results in the rapid spread (or drive) of the bacterium throughout the insect population. *Wolbachia* colonizes salivary glands, oocytes, gut and other organs without affecting lifespan (9). *Wolbachia* infection has an important beneficial effect for the insect, because it stimulates innate immunity preventing replication of RNA viruses. Consequently, *Wolbachia*-infected mosquitoes are unable to spread Dengue and Zika viruses in their saliva (9, 10).

A strain called wMel obtained from *Drosophila melanogaster* was cultured for two years inside a mosquito cell line and then microinjected into *Aedes aegypti* eggs (9). Once *Aedes* infected with *Wolbachia* is released it spreads rapidly throughout the population driven by the cytoplasmic incompatibility mechanism. The population levels of *Aedes aegypti* are maintained but are no longer able to transmit disease. Infected mosquitoes of both sexes can be released into the wild because females will not transmit the viruses. This appears to be a very promising approach and small-scale releases into cities have already been carried out in Cairns and Rio de Janeiro, and much larger ones are planned in Brazil.

Another gene-drive approach which is still in its infancy, and so far has only been tested in the malaria mosquito, is based on the new CRISPR/Cas9 gene editing technology. Ethan Bier at the University of California San Diego has devised methods by which DNA segments containing both the Cas9 nuclease and a guide RNA flanked by segments of DNA on either side of the cleavage site will insert at desired targets in the germ line of *Drosophila* and *Anopheles*. Once inserted, it is enough to have the gene in one chromosome, since it will edit a wild-type chromosome at the same exact site, converting a heterozygote into a homozygote and rapidly spreading through the population (11). Genes that provide immunity to the malaria parasite have been inserted into this gene-drive cassette in *Anopheles*. These tests are purely experimental at the time of writing (November 2016) and these fruit flies or mosquitoes have not been released into the wild as they are expected to spread rapidly. This gene-drive method will probably be impractical in its present form because resistance will eventually arise by insertions and deletions that are no longer recognized by the guide RNA. However, it serves to illustrate the awesome power of the emerging gene editing technology.

Fortunately, a Zika virus vaccine is expected to be simple to prepare. Several approaches have already been shown to be effective in monkeys. Yellow fever was defeated by a vaccine. The only Nobel Prize awarded for a vaccine was that of Max Theiler in 1951, who pioneered the use of chicken eggs to grow Yellow fever virus.

Conclusion

High-throughput DNA sequencing will make it possible to identify a large number of babies with disease caused by loss-of-function mutations in a single gene allele. The Zika virus epidemic will result in many persons with brain defects. It seems to me that the sanctity of human life will have to be defended vigorously from a global secular culture of death openly promoting euthanasia, if we are to avoid the specter of eugenics and infanticide.

In the encyclical *Evangelium Vitae* (12) Saint John Paul wrote: "Every individual, precisely by reason of the mystery of the Word of God who was made flesh (cf. Jn 1:14), is entrusted to the maternal care of the Church. Therefore every threat to human dignity and life must necessarily be felt in the Church's very heart; it cannot but affect her at the core of her faith in the Redemptive Incarnation of the Son of God, and engage her in her mission of proclaiming the Gospel of life in all the world and to every creature (cf. Mk 16:15). Today this proclamation is especially pressing because of the extraordinary increase and gravity of threats to the life of individuals and peoples, especially where life is weak and defenceless. In addition to the ancient scourges of poverty, hunger, endemic diseases, violence and war, new threats are emerging on an alarmingly vast scale." *Verbum sapientiae*, wise words indeed. The protection of the weak is as necessary now as ever.

References

1. Zaidi *et al.* (2013). *De novo* mutations in histone-modifying genes in congenital heart disease. *Nature 498*, 220-223.
2. Sanders *et al.* (2012). *De novo* mutations revealed by whole-exome sequencing are strongly associated with autism. *Nature 485*, 237-241.
3. Homsy, J. *et al.* (2015). *De novo* mutations in congenital heart disease with neurodevelopmental and other birth defects. *Science 350*, 1262-1266.
4. Fauci, A.S. and Morens, D.M. (2016). Zika virus in the Americas – Yet another arbovirus threat. *N. Engl. J. Med. 374*, 601-604.
5. Mlakar, J. *et al.* (2016). Zika virus associated with microcephaly. *N. Engl. J. Med. 374*, 951-958
6. Wu, K.Y. *et al.* (2016). Vertical transmission of Zika virus targeting the radial glial cells affects cortex development of offspring mice. *Cell Res. 26*, 645-654.
7. Zettel, C. and Kaufman, P. (2008). Yellow fever mosquito *Aedes aegypti* (Linnaeus) http://entnemdept.ufl.edu/creatures/aquatic/aedes_aegypti.htm
8. McBride, C.S. *et al.* (2014). Evolution of mosquito preference for humans linked to an odorant receptor. *Nature 515*, 222-227.
9. Walker, T. *et al.* (2011). The wMel *Wolbachia* strain blocks dengue and invades caged *Aedes aegypti* populations. *Nature 476*, 450-453.
10. Carneiro Dutra, H.L. *et al.* (2016). *Wolbachia* blocks currently circulating Zika virus isolates in Brazilian *Aedes aegypti* mosquitoes. *Cell Host Microbe 19*, 771-774.
11. Gantz, V.M. and Bier, E. (2016). The dawn of active genetics. *Bioessays 38*, 50-63.
12. Ioannes Paulus PP. II (1995). *Evangelium Vitae* Encyclical http://w2.vatican.va/content/john-paul-ii/en/encyclicals/documents/hf_jp-ii_enc_25031995_evangelium-vitae.html

The Challenges and Chances of Complexity: Implications for Governance and Ethics

Wolf J. Singer[1]

Biological evolution has brought forth systems of ever increasing complexity. This trend culminated in the emergence of highly structured societies, also addressed as super-organisms, whose complexity exceeds that of their constituting components and reached a maximum in human societies. Why did evolution take this direction? The most likely reason is that increasing complexity enhances fitness. One important fitness factor is the cognitive and executive abilities of organisms, functions that depend to a large extent on the information processing capacity of neuronal networks. These functions permit organisms to generate detailed models of the world and to design well-adapted coping strategies. Enhancing cognitive functions obviously requires investment in the complexity of sense organs and nervous systems.

In simple organisms the components of the nervous systems, the neurons, interact mainly serially, relaying information sequentially from sensory organs to effector systems. Consequently the emerging dynamics have low dimensionality and complexity even though the nervous systems may consist of a large number of components. While such feed-forward architectures are conserved in the brains of virtually all species, they prevail in simple organisms such as molluscs and insects. As a consequence, the ability of these organisms to process complex constellations of sensory signals is limited to solutions for special problems. Similar principles of information processing are realized in artificial systems, known as deep learning networks, that have revolutionized the field of artificial intelligence and outperform human cognitive abilities in some selected domains. These systems capitalize on the power and speed of modern computers and the availability of immense databases for the training of artificial networks. However, in numerous domains they fall short of the performance of biological sys-

[1] Max Planck Institute for Brain Research (MPIB); Ernst Struengmann Institute for Neuroscience (ESI) in Cooperation with Max Planck Society; Frankfurt Institute for Advanced Studies (FIAS).

tems because they lack certain architectural features that characterize more evolved nervous systems.

The decisive difference is recurrence and re-entry. In the more evolved systems the components are coupled reciprocally rather than only serially. The flow of information is no longer unidirectional from low to high processing levels, from sensory organs to effectors. Rather, components interact with one another already within each of the processing levels and these levels are in addition coupled via feedback loops, allowing for bidirectional flow of information. Systems with such features develop extremely complex, non-linear dynamics and are capable of self-organization. They can generate a very large number of distinct spatially and temporally structured patterns of activity: Their non-linear dynamics allow them to explore a very high dimensional state space and to assume a virtually infinite number of different states. Evolution discovered the power of these principles early on and selection pressure led to a massive increase of processing architectures, that allow for recurrence and self-organization. Examples are the extremely complex interaction networks that have emerged in higher organisms at all levels of organization: already genes interact with one another through extremely complex molecular signalling systems and mutually influence each others' expression. It is mainly the architecture of this interaction network that accounts for the fact that a relatively small set of similar genes can instruct the development of very different organisms. These gene-gene interactions orchestrate the species-specific expression pattern of the genes. Drosophila, the fruit fly, has more or less the same set of coding genes as us, but the interaction network controlling the expression of these genes differs. Very similar principles govern the interactions in metabolic networks, in the immune system and, above all, in the neuronal networks of highly evolved organisms.

In the case of neuronal systems, simple feed-forward interactions are complemented more and more by reciprocal interactions between the nodes of the networks. Neurons interact reciprocally with one another both within and across processing levels. This connectivity motive is particularly pronounced in the cerebral cortex and the hippocampus, structures that appeared in rudimentary form first in reptiles. Once these structures had been developed, further increases in the brain's complexity consisted essentially in a massive expansion of the cerebral cortex. This suggests that the functions associated with the evolution of structures capable of supporting recurrent processing are scalable and very effective in enhancing biological fitness.

We are still far from fully understanding the functions realized on the basis of the extremely complex, non-linear and high dimensional dynamics that evolve in the recurrent networks of the cerebral cortex. However, we begin to see that the astounding cognitive and executive capacities of highly evolved brains are due to computations that take place in the cerebral cortex and capitalize on the dynamics and self-organizing properties of this structure: the ability to store an immense quantity of information in a high dimensional dynamic space and to allow for ultrafast retrieval of this information, the generation of associations between experiences gathered in different sensory modalities – a prerequisite for abstraction – the generation of complex patterns for the control of executive functions, the encoding of contents in abstract symbolic format and finally, in the case of humans, the generation of a highly differentiated, rule-based communication system, our grammar- and syntax-based language. It goes without saying that these functions have a substantial survival value. As the acquisition of these highly differentiated cognitive functions is a direct consequence of the increasing complexity of underlying brain processes, it is plausible that selection pressure favoured the evolution of ever more complex brains. Moreover, in order to fully exploit the enhanced information processing capacities of highly evolved brains, coevolution may have led to more versatile and hence more complex sensory organs and effector systems.

In conclusion, evidence suggests that increasing complexity endows organisms with improved cognitive and executive functions that in turn allow them to cope more effectively with the challenges of survival in a rapidly changing, dangerous and competitive environment.

However, at first sight this interpretation seems at odds with the intuition that increasing complexity is also likely to enhance the vulnerability of the systems and thereby reduces fitness. The more components a system has, the higher the probability that one of them will fail. The denser and more complex the interactions between components are, the higher the probability that local failures lead to a catastrophic collapse of the whole system, in particular when the systems have highly non-linear dynamics. In this case, small local disturbances can undergo massive amplification and propagate throughout the entire interaction network with deleterious consequences for the functions of the whole system.

Interestingly, however, the intuition that complexity and vulnerability are positively correlated may not be true. There is evidence that increasing complexity could, in itself, be a fitness factor that enhances the resilience and robustness of systems. In principle, there are two strategies to augment the resilience of systems. One consists in increasing redundancy by multiplying critical components. Until recently this has been the most common strategy applied in technical systems. Another, and at first sight contra-intuitive strategy, is to increase the complexity of systems. As mentioned above, truly complex systems consist in reciprocally interacting components and exhibit non-linear dynamics. Such systems are capable of self-organization and self-healing. They are able to compensate by reorganization for the drop out of individual elements. As a consequence, they often undergo "graceful degradation" of their function if some of their components fail, but they rarely lose all functions. Simple systems with unidirectional flow of information within hierarchical architectures and mainly linear dynamics, by contrast, cannot self-organize. Here the failure of a component of the processing stream leads to a complete loss of the corresponding function. The resilience of such systems can only be enhanced by increasing redundancy, a strategy that requires massive investment in hardware. Thus, increasing complexity may actually have served fitness in two ways. It allowed realization of sophisticated cognitive and executive functions and, at the same time, it enhanced the robustness of the organisms by endowing them with the capacity to self-organize. And interestingly, this strategy to enhance resilience by increasing the complexity of network interactions by recurrence and re-entry is not confined to the evolution of individual organisms. As far as biological evolution is concerned, it is probably also the reason for the emergence of superorganisms such as colonies of bees and ants, in which the agents are interacting reciprocally through highly structured communication networks. And last but not least, the generation of social and economic networks formed by social animals, which reached a maximum of complexity in human societies once cultural evolution complemented biological evolution, are also likely to have the same reason: increasing resilience through cooperation and self-organization.

However, there is also a downside of complex systems with highly non-linear dynamics, in particular when it is required to control their future trajectories. The very same mechanisms that support their self-organizing capacity and resilience towards disturbances and make them robust and resistant to the failure of components and adverse influences from outside, also make it very difficult to control their collective dynamics.

Reciprocal coupling, recurrence and re-entry are also distinctive features of our social, political, economic and financial systems. Accordingly, these systems also exhibit highly non-linear dynamics and self-organizing capacities – and as globalisation proceeds and digital communication networks proliferate, their complexity increases with unprecedented speed. The problem with such complex systems is that their future development cannot be reliably predicted. One popular example is the dynamics of stock markets. For the same reason it is very hard to control the long-term behaviour of these systems. Manipulating the activity of individual nodes or the coupling strength of interactions can lead to entirely unforeseen responses of the systems because of their non-linear dynamics. Thus, top down control and dirigisme are ineffective governance strategies when one has to do with complex systems endowed with strong self-organizing capacities. One way out is to destroy their capacity for self-organization. This can be achieved by abolishing interactions between the components and aligning them in hierarchical structures in which information flow is unidirectional. In this case the activity of individual nodes can be reliably controlled in a strictly top-down regime – a strategy opted for by totalitarian systems. This, however, sacrifices the resilience and robustness inherent in self-organizing systems and is likely to be efficient only for the governance of relatively simple systems, whose dynamics are essentially linear. Historical evidence about the fate of totalitarian systems suggests, that dirigisme is an inappropriate strategy once systems reach a critical threshold of complexity and defy analytical approaches.

These notions about the properties of complex systems have far-reaching consequences for our attempts to take responsible action and to design effective governance regimes. In essence we are trapped in a tragic circle. We cannot stop acting. Thus, we continue to permanently interfere with the systems in which we are embedded and to contribute to their future trajectories. At the same time we know that we cannot really control the systems that we have created – a dilemma to which there is no simple solution.

Even before the theory of complex systems provided explanations for the difficulty to control the dynamics of non-linear systems, humans experienced that they are embedded in a world whose evolution they can neither understand nor effectively control. This collective intuition of being thrown into an uncontrollable world whose properties cannot be deduced from the properties of the components – another important characteristics of complex, self organizing systems – is probably one reason for postulating the existence of transcendental forces that are endowed with the meta-intelligence and power required to stabilize the world and to determine the fate of individuals.

In the following I shall examine to which extent it is possible to derive some rules of conduct from the humbling notion that we are embedded in a complex systems, whose stability depends on the principles of self-organization and whose future trajectories are not determinable. Such rationally deducted rules could perhaps serve as mosaic stones for the development of secular ethics.

First and above all we need to internalize the insight that we are actors in a system whose trajectory is not readily predictable and that this uncertainty is not simply due to incomplete knowledge of initial conditions but is constitutive of complex systems with highly non-linear dynamics. This insight calls for humbleness and should nurture scepticism vis-à-vis affirmative promises and simple recipes. The problem of unpredictability can be alleviated to some extent by simulating possible outcomes with computational models – as is currently done to derive prognoses on climate change, but in principle this approach too cannot provide more than probabilities. One option to cope with these uncertainties and the resulting feeling of helplessness is to foster confidence in the stability and resilience of complex, self-organizing systems. This confidence is warranted since we owe our existence to the robustness of such systems. However, in order to justify this confidence, we need to assure that the systems in which we evolve preserve their self-stabilizing property.

Fortunately, some of the mechanisms supporting self-organization are known and this allows us to deduce by reasoning which prerequisites should be fulfilled to facilitate self-organizing processes. One of these prerequisites, already alluded to above, is to ensure dense and reliable communication among the nodes of the network. Here it is imperative to assure that the flow of information is not distorted or compromised, as this would jeopardize the self-organizing capacity of the system. Nodes of the network must be reliable, they must not lie. If the forager bees lied to the hive about the location of resources, the whole system would rapidly break down. Furthermore we are well advised to not interfere with the existing systems too much and to induce only incremental changes in order to avoid abrupt bifurcations and catastrophic instabilities. This calls for a conservative attitude towards change, diligent use of resources and preservation of interaction architectures that have proven efficient in the past. And most importantly, monitoring systems have to be implemented that evaluate the state of the system and keep track of its evolution. Ideally, such evaluation systems should take into account both the wellbeing of the individual nodes and the stability of the whole system in order to allow adjustments of the system's interaction architecture. Unlike the rulers of hierarchical systems these evaluation systems do not have to get involved in the micromanagement of the system. They only have to provide continuous feedback about the state of the system and assure that the consequences of spontaneously occurring or induced changes in the system's architecture are tracked at short intervals. It would then suffice to reinforce and consolidate those interactions that have enhanced wellbeing and stability and to weaken interactions that had adverse consequences. In a sense this would mimic the evolutionary mechanisms that have been so successful in bringing about stable and highly complex systems. Our brains are organized in this way. They possess evaluation systems that monitor the internal state of the brain and the success or failure of actions. These evaluation systems, also addressed as reward systems, supervise the experience-dependent changes in the system's functional architecture, i.e. changes in the strength of coupling among nodes that are the basis of learning processes. Features of the functional architecture that favour positive behavioural outcomes become reinforced and those having adverse effects get suppressed. The similarity of this self-organizing optimization process with evolutionary mechanisms is obvious.

The challenge for societies opting for such self-organized governance structures is of course to define the evaluation criteria and the variables to be monitored. Furthermore, mechanisms have to be implemented that allow for the continuous adjustment of the system's interaction architecture. As a first step it would be interesting to examine to which extent the various forms of democracy and economic systems already rely on such evolutionary mechanisms of self-organization and optimization. Changes of interaction architectures are constantly induced by legislation, economical decisions and spontaneous fluctuations and the consequences of these changes on the state of the system are monitored by ballots and elections, causing stabilization of architectures perceived as advantageous.

However, there is a decisive difference between the self-organizing mechanisms that supported biological evolution and those that govern our fate since the beginning of cultural evolution. As far as we know, biological evolution had no goal and the agents promoting it had no insight in their destiny. Human agents, by contrast are aware of being able to intentionally interact with their environment, to articulate goals and to act accordingly. This endows them with responsibility for the evolutionary trajectory of the systems that they generate and keep in motion. Thus, even though we are still just components of an immensely complex self-organizing system, we want this process to be goal directed. And this imposes upon us the obligation to acquire as much knowledge as possible about the system that we evolve in and to use this knowledge for the design of interaction architectures that serve both the wellbeing of the components and the stability of the whole system. In addition, because we are intentional agents endowed with insight we need to identify the rules of conduct that assure the stability of our systems and we need to comply with them. We need to behave as moral agents and the rules that we identify should become the pillars of a secular ethics. Some of these rules are easy to identify and it comes as no surprise that they are virtually identical to the principal commandments found in the world religions. Apparently collective experience about stability generating rules of conduct has converged between different cultures. However, these rules of conduct often reflect the particular conditions and needs of human communities that evolved within rather different biotopes. Thus, not all of these rules are readily generalizable and some of them are perceived by members of the respective other culture as a consequence of false beliefs. As globalisation proceeds, these cultural idiosyncrasies become a major source of conflict. Therefore, attempts have to be intensified to arrive at a consensus on the most important rules of conduct. It is my conviction that such a process can only converge if arguments are based on evidence and reasoning rather than beliefs – and this is where cooperation between the natural sciences and the humanities is urgently needed.

My Sixty-six Years of Medical Research

Michael Sela[1]

In preparing this presentation, I was encouraged by our Chancellor who thought that health and healthy aging are relevant to the notion of sustainability. Most of my research over more than six decades has been in the field of proteins and protein models, namely polymers of amino acids, and all of it was related to medical research. Later on I worked mainly in immunology, where I was responsible for the creation of the notions of the immunogen and of immunogenicity; on a more applied level, I developed the first synthetic antigens and their use as drugs. Thus I found myself in what is now called translational research. My perspective on sustainability thus is founded on my experience in science in general, and in immunology and health in particular. Sustainability, in my view, relates to the individual, to the scientist, and to humanity – the beneficiary of science.

First, let me tell you my essential advice to a young scientist, but which is actually valid for any scientist, and indeed for the sustainability of any creative individual.

1. First of all curiosity. My definition of happiness is the capacity to be curious. If you lose curiosity, you become a vegetable.
2. Optimism. You have to believe and to be enthusiastic about what you believe.
3. Perseverance. Not always everything works well. Your optimism will help you to persevere, even though things look grim. A sustained effort is essential.
4. Truth. Stick to it, because the alternatives are more dangerous and end in catastrophies.
5. Strive for excellence. You must believe in what you are doing, and set your goals at the highest level.

For most individuals, after many years of research, publication in an impressive journal seems the end of the road, but this is not true, certainly not in translational research, because the next step – the development of the fruits of research – is most important, and you must follow it closely. But

[1] Weizmann Institute of Science, Rehovot, Israel.

when your study reaches a product, my advice is: remove yourself from the financial aspects, because others understand them much better than you.

The translation of research into products is important both for the individual and for humanity as a whole.

Unfortunately, it is becoming more and more difficult and prohibitively expensive to reach new drugs: there are two ways to consider.

1. Try to apply known drugs to new uses: drugs that have been successful for another indication, and even candidate drugs that were not successful for the purpose for which they were created. What people call: "New tricks for old drugs".
2. When two drugs, each used separately, have only weak effects, their combination may have a strong synergistic effect. Indeed, my laboratory has succeeded in this regard in developing three successful drug combinations against three different cancers. Nevertheless, I hasten to stress that these are successful treatments in improving quality of life, but none of them is a cure.

I would like to distinguish between discoveries and inventions.

The above-described treatments of different kinds of cancer are discoveries – both the relevant antibodies and the chemotherapeutic drugs existed before we learned to exploit them for new uses. In another case, the drug against multiple sclerosis, denoted Copaxone, is an invention, as it did not exist before our research, until it was synthesized as a copolymer of amino acids.

Let me now turn to the sustainability of the human species. Crucial responsibility for the sustainability of mankind and on this planet is healthy aging. In recent years, there has been a tendency to define aging as a disease, with all the advantages the definition brings to the patient in terms of drugs and treatments. But aging has a serious impact on the sustainability of society: as the percentage of older people increases continuously, and the elderly become a burden on society, their health must be improved, first of all for them individually, but also for society as a whole. Thus, global health becomes a significant problem even as we discuss sustainability as a whole.

Many ways can help humans and human society to sustain health, like diet, physical exercise and sports, a frugal lifestyle, etc., but I want to mention here – specifically – some dramatic improvements in fighting diseases by using immunology, and I refer both to neuroimmunity, and to immunotherapies against cancer. These are not only in individual cases, but may improve the outcome for a healthier and longer life, influencing positively the sustainability of mankind on this planet.

Plastics in the Oceans: Perspectives for Their Biodegradation[1]

Rafael Vicuña

Introduction

I devoted 25 years of my career as a research scientist to study the biodegradation of lignin, by far the most recalcitrant natural polymer on earth. Today, I will refer to the biodegradation of plastics, which are highly recalcitrant synthetic polymers. More specifically, since this plenary session is about science and sustainability, I would like to address a topic of increasing concern, which is the heavy contamination of the oceans with plastic material. This appears as a paradigmatic case in which scientific knowledge is deemed to play an essential role in the design of public policies for the protection of the environment.

I would like to start my presentation by quoting Pope Francis in his encyclical *Laudato si'*, precisely devoted to the environment and human ecology. In §21 of the encyclical, the Pope asserts that each year hundreds of millions of tons of waste are generated, much of it non-biodegradable. Then, in §174 he adds that the growing problem of marine waste and the protection of the open seas represent particular challenges. As you well know, *Laudato si'* also includes an urgent appeal to protect our common home by bringing the whole human family together to seek a sustainable and integral development.

Assessing the problem

Now, I will say a few words concerning the plastic industry and the final destination of plastic waste. Plastics are a suitable material for multipurpose use due to their low cost, high durability and resistance to physical breakdown. At present, global plastic production reaches about 300 million metric tons per year.[2] Unfortunately, disposal of waste plastic is problematic due to its inherent resistance to decomposition. Some plastic is recycled, although the majority is placed in landfills where it may take centuries to breakdown.

[1] This text corresponds to the transcript of the oral presentation at the Plenary Session.

[2] Cressey, D. The plastic ocean. *Nature* 536, 263-265, 2016.

Of particular concern are plastic debris that end up in the marine environment. This outcome may result from accidental loss, deliberate release or poor waste management practices. As revealed in a recent study published in *Science*, an estimated 4.8-12.7 million tons of plastics entered the oceans from land-based sources in 2010.[3] This is equivalent to one municipal garbage truck dumping its content in the ocean every minute. If ocean-based sources such as fishing and shipping are included, the input of plastic increases by 20%.[4]

Marine plastic debris include mainly beverage bottles, bags, toys, tires, cigarette filters, nets, ropes, traps, fishing lines, etc. However, although less evident to visual inspection, a severe impact is exerted by microplastics, with a particle size of up to 5 mm. These may consist of fragments deriving from larger plastics, microbeads used in cosmetics, resin pellets employed in the production of plastics (so-called "nurdles"), remnants of ship coatings, etc.

There have been some surveys to estimate the amount of plastic debris in the ocean. For example, a study published by Eriksen *et al.* in PLOS One a couple of years ago,[5] shows that there are more than 5 trillion plastic pieces weighing over 250,000 tons floating in the ocean. Of these, 92% correspond to microplastic particles within a size range between 0.33 and 4.75 mm, which comprises 13% of the total by weight. This figure does not include plastics in the seabed or particles below 0.33 mm.

The same group, as well as others, have found that plastics of all sizes concentrate mainly near five ocean gyres, where converging surface currents trap and mobilize floating debris towards the vortex centers. The highest concentrations are found at the North Pacific gyre, also known as the Great Pacific garbage patch. Plastic debris also cluster along the coasts near human communities. For these studies, plastics were classified in four size classes: 0.33 to 1 mm, 1 to 5 mm, 5 to 200 mm and bigger than 200 mm.

[3] Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L. Plastic waste imputs from land into the ocean. *Science* 347, 768-771, 2015.

[4] Andrady, A.L. Microplastics in the marine environment. *Mar. Pollution Bull.* 62, 1596-1605, 2011.

[5] Eriksen, M., Lebreton, L.C.M., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., Galgani, F., Ryan, P.G, Reisser, J. Plastic pollution in the world's oceans: More than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. *PLOS One* 9(12): e111913. doi:10.1371/journal.pone.0111913

There is another global inventory of floating plastic debris published by van Sebille *et al.*,[6] which yielded a higher limit of 51 trillion pieces weighing 236,000 tons. Both studies agree on a similar figure for the total weigh of plastic debris floating in the ocean: about 250 kilotons. But this is only between 1 and 2% of the global plastic waste estimated to have entered the ocean in the year 2010. The question is then: Where is the missing plastic litter? Four main possible sinks have been proposed for the substantial losses of floating plastic from the surface: shore deposition, nano fragmentation, biofouling and ingestion. However, as suggested by Woodall *et al.*,[7] deep-sea is the most likely fate of microplastic debris.

We may ask how do plastics affect the marine environment. They do so in various ways: entanglement of birds, fish, seals and whales in fishing gear (lines and nets); floating plastics transport microbial communities to new environments, threatening native ecosystems; micro plastics decrease growth of fish larvae;[8] plastics are ingested by fish and seabirds. It has been found that zooplactivorous fishes may contain up to 30% plastics in their gut.[9] On the other hand, plastics in the ocean adsorb persistent hydrophobic organic pollutants such as DDT, PCBs, PBDEs, which when ingested by the trophic fauna bioaccumulate in the food chain. Moreover, plastic manufacture involves the use of potentially toxic additives, such as antioxidants, UV stabilizers, flame retardants and antimicrobial agents. Since most of these chemicals are lipophilic, they penetrate cell membranes when ingested.[10]

All these facts confirm that we are in the presence of a threat not only to the environment, but also to animal and human health. According to a study published in the journal *Australian Quarterly*, more than 100,000 sea

[6] van Sebille, E., Wilcox, C., Lebreton, L., Maximenko, N., Hardesty, B.D., Franeker, J.A., Eriksen, M., Siegel, D., Galgani, F., Law, K.L. A global inventory of small floating plastic debris. *Environ. Res. Lett.* 10, 124006, 2015.

[7] Woodall, L.C., Sanchez-Vidal, A., Canals, M., Paterson, G.L.P., Coppock, R., Sleight, V., Calafat, A., Rogers, A.D., Narayanaswamy, B.E., Thompson, R.C. *R. Soc. Open Sci.* 1, 140317, 2014.

[8] Lönnstedt, O.M., Eklöw, P. Environmentally relevant concentrations of microplastic particles influence larval fish ecology. *Science* 352, 1213-1216, 2016.

[9] Lusher, A.L., McHugh, M., Thompson, R.C. Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. *Mar. Pollution Bull.* 67, 94-99, 2012.

[10] Teuten, E.L., Saquing, J.M., *et al.* Transport and release of chemicals from plastics to the environment and to wildlife. Phil. Trans. R. Soc. B 364, 2027-2045, 2009.

animals die each year from eating or being caught in plastic debris.[11] There are also recent publications demonstrating the consumption of plastic by deep sea fauna[12] and also the presence of plastics in seafood intended for human consumption,[13] confirming that the environmental problem is also turning into a human health hazard.

What are the possible solutions for the problem of plastic contamination of the oceans? First, public policies and agreements to prevent marine pollution, of which there are several. The question is to what extend the citizens of all signing nations comply with these agreements.[14] In addition, a better waste management is required, including cutting down the amount of plastic microbeads in personal care products. Third, plastic recycling, although it has a cost because it requires sorting different plastics comprising the waste. Also, clean up of existing marine debris: various countries and NGOs perform periodical clean-up programs at a high cost. Efforts should concentrate near the coasts before it sinks or is ingested by wildlife. And finally, use of biodegradable plastics and polymer blends: for example, starch- and cellulose-based plastics, bio-based polyesthers such as polylactic acid, polyhydroxybutirate, etc.

[11] Wilks, S. *Australian Quarterly* 78, 2006. (Cited in Martinez, E., Maamaatuaiahutapu, K., Taillandier, V. Floating marine debris surface drift: convergence and accumulation toward the South Pacific subtropical gyre. *Mar. Pollution Bull.* 58, 1347-1355, 2009.

[12] Taylor, M.L., Gwinnett, C., Robinson, L.F., Woodall, L.C. Plastic microfibre ingestion by deep-sea organisms. *Scientific Reports*, 6:33997, DOI: 10.1038/srep33997

[13] Rochman, C.M., Tahir, A., Williams, S.L., Baxa, D.V., Lam, R., Miller, J.T., Teh, F-C, Werorilangi, S., Teh, S.J. Anthropogenic debris in seafood: Plastic debris and fibers from textiles in fish and bivalves sold for human consumption. *Scientific Reports*, 5:14340, DOI: 10.1038/srep14340

[14] Among them, the International Convention for the Prevention of Pollution from Ships, so called MARPOL convention adopted in 1973 by the International Maritime Organization, the Regional Seas Programme launched in 1974 by the UNEP, Global Programme of Action for the Protection of the Marine Environments from Land-based Activities created by UNEP in 1995, Marine Strategy Framework Directive (EU 2008), Sustainable Development Goals of the UN (2015, #14 addressed to protect life under water).

Plastic biodegradation[15]

First, a few words about the structure of plastics. There are those with a carbon-carbon backbone, such as polyethylene and polystyrene. These are highly resistant to microbial attack, most likely because during their short residence time in natural environments evolution could not design new degradative enzymes. Besides, their solid nature results in an extremely low exposure to potential enzymes. However, when long polymers are fragmented by abiotic means, small oligomers can enter the cell where they are metabolized. On the other hand, there are plastics with ester (polyethylene terephthalate, PET) and amide (nylon, polyurethane) bonds, which are attacked by extracellular hydrolases. For example, PET can be hydrolyzed by cutinase, an enzyme that cleaves the esther linkages in cutin, the main constituent of the plant cuticle. In this case, one of the products is further metabolized and enters the Krebs cycle. On the other hand, Yoshida *et al.* recently published the degradation of the same polymer by a single bacterium which produces two enzymes, yielding aliphatic and aromatic monomers, both of which are used as carbon source for growth.[16]

Another example of a degradable plastic is polyurethane, which possesses amide and ester bonds. Both are hydrolysable and therefore the type of product will depend on the specificity of the enzyme catalyzing bond cleavage, which can be a urease, esterase or protease.

Decay of plastics in the ocean

In marine environments, plastic deterioration takes place by a combination of four mechanisms: photo degradation, thermal degradation, mechanical action and biodegradation. Weathering of plastics by sunlight and mechanical action leads to the production of smaller fragments and particles, thus increasing the surface area susceptible to microbial attack.

In particular, light and temperature lead to the formation of highly reactive free radicals, which can be either carbon or oxygen centered. Among the latter, peroxyl and hydroxyl radicals are the most reactive. Some reac-

[15] For recent review, see Muthuk, S., Veerappapillai, S. Biodragradation of plastics: A brief review. *Int. J. Pharm. Sci. Rev. Res.*, 31(2), 204-209, 2015; Ghosh, S.K., Pal, S., Ray, S. Study of microbes having potentiality for biodegradation of plastics. *Environ Sci Pollut Res.* 20, 4339-4355, 2013; Tokiwa, Y., Calabia , B.P., Ugwu, C.U., Aiba, S. Biodegradability of plastics. *Int. J. Mol. Sci. 10*, 3722-3742, 2009.

[16] Yoshida, S., Hiraga, K., Takehana, T., Taniguchi, I., Yamaji, H., Maeda, Y., Toyohara, K., Miyamoto, K., Kimura, Y., Oda, K. A bacterium that degrades and assimilates poly(ethylene terephthalate). *Science* 351, 1196-1199, 2016.

tions end up with the fragmentation of the polymer, sometimes possessing alcohol or ketone groups.[17] Others are crosslinking reactions that lead to products of higher molecular weight. Typically, an oxygen-centered radical may react with a non-radical plastic polymer producing ketone and olefin fragments, plus a carbon centered radical that will in turn react with oxygen to produce a peroxi radical, and so on. It is expected that the small fragments produced in reactions involving free radicals enter the cells of microorganisms to be further biodegraded to CO_2 plus water.

What do we know about marine microorganisms metabolizing plastic-derived oligomers? At present, not much. However, there is promising work conducted by the group led by Erik Zettler, from Woods Hole, Massachusetts, which refers to the characterization of the microbial community that colonizes microplastics in the ocean. He has called these communities the platisphere.[18] Platisphere communities vary with location, season and polymer type.[19] Microorganisms differ from those of the surrounding seawater, being bacillus and diatoms the most abundant. It has been calculated that the platisphere represents about 6% of the total mass of microplastic debris. It is still debatable whether the biofilm might protect plastic from photo degradation. However, pits conforming to bacterial shape visualized on the surface strongly suggest plastic biological decay. In addition, ribosomal RNA surveys confirm the presence of hydrocarbon-degrading bacteria.

This work is only starting and there is much to be learned with respect to biochemical mechanisms leading to plastic degradation by these communities. Whatever these mechanisms may be, plastic biodegradation is an intrinsically slow process, even under ideal laboratory conditions. One may ask then what can be done to make plastics more prone to biodegradation not only in the ocean but in any environment and thus decrease their harmful impact.

There are several options to reach this objective. One is to use only plastics of petrochemical origin that are biodegradable, as the ones mentioned previously. There is also the possibility of using biodegradable plas-

[17] Gewert, B., Plassmann, M.M., MacLeod, M. Pathways for degradation of plastic polymers floating in the marine environment. *Environ. Sci.: Processes Impacts*, 17, 1513-1521, 2015.

[18] Zettler, E.Z., Mincer, T.J., Amaral-Zettler, L.A. Life in the "Plastisphere": Microbial communities on plastic marine debris. *Environ. Sci. Technol.* 47, 7137-7146, 2013

[19] Amaral-Zettler, L.A., Zettler, E.R., Slikas, B., Boyd, G.D., Melvin, D.W., Morrall, C.E., Proskurowski, G., Mincer, T.J. The biogeography of the Plastisphere: implications for policy. *Front Ecol Environ* 13(10), 541-546, 2015.

tics based on starch and cellulose, or plastics based plastics. Another option is to blend conventional plastics with bio-based biodegradable plastics, or use oxo-biodegradable plastics, so-called because they contain pro-oxidant additives (organic salts of Fe, Co, Ni or Mn) that facilitate weathering by light and heat.[20] Bio-based plastics seem to be a promising solution. However, their actual presence in the market is only marginal.

On the other hand, we must keep in mind that bio-based plastics are not a panacea, as asserted in a recent report entitled "Biodegradable plastics and marine litter" issued by UNEP – the United Nations Environmental Program.[21] According to this account, among other drawbacks, bio-based plastics tend to be more expensive; they must be separated from fossil fuel-based plastics for recycling; their efficient biodegradation occurs under conditions that are rarely, if ever, met in the marine environments; and labelling a product as biodegradable may result in a greater inclination to litter on the part of the public. Only time will tell whether bio-based plastics succeed in replacing non-hydrolysable synthetic plastics.

Final remarks

To conclude, it is worthwhile to outline some future tasks that may be relevant in this very critical issue of plastics in the ocean. First, reiterate the need for better waste management, for recycling, for cleaning-up the existing marine debris and for proper public policies to prevent marine pollution. Confidently, the latter must be based on scientific evidence.[22] Then, to continue studies of plastic biodegradation in the oceans. To date, most work reported in the literature corresponds to experiments conducted under conditions that are not relevant to the marine environment. Finally, to study the fate and environmental impact of plastic biodegradation by-products (some may be toxic or more recalcitrant) and also of additives and persistent organic pollutants that sorb to the plastics in the ocean.

[20] Deconinck, S., Dewilde, B. Benefits and challenges of bio- and oxo-degradable plastics. Final Report Stydy DSL-1, 118p, 2013.

[21] Biodegradable plastics and marine litter. Report issued by UNEP – the United Nations Environmental Program. ISBN: 978-92-807-3494-2, Job Number: DEP/1908/NA, 2015.

[22] Rochman, C., M. Strategies for reducing ocean plastic debris should be diverse and guided by science. *Environ. Res. Lett.* 11, 041001, 2016.

HUMAN SCIENCES SESSION

Presentation on the Current Status of Organ Donation and Transplantation Around World – With the Dilemma of Organ Trafficking and Transplant Tourism

Francis L. Delmonico

Organ transplantation, one of the medical miracles of the twentieth century, has prolonged and improved the lives of hundreds of thousands of patients worldwide. The many great scientific and clinical advances of dedicated health professionals, as well as countless acts of generosity by organ donors and their families, have made transplantation not only a life-saving therapy but a shining symbol of human solidarity. Yet these accomplishments have been tarnished by the trafficking in human beings who are used as sources of organs and of patient-tourists from rich countries who travel abroad to purchase organs from poor people.

These two pictures contrast the reality of organ transplantation in 2016.

On the left, Doctor Joseph E Murray is receiving the Nobel Prize in Medicine for his contribution in kidney transplantation. The nobility of his contribution is conveyed by acknowledging the benefit of organ transplantation in restoring individuals to well-being.

On the right, bonded laborers are shown with their scars following kidney removal. They are hoping to release themselves from such bondage having parted with a kidney – sold to affluent individuals who can come to Pakistan for illegal transplantation.

The picture on the right of organ trafficking is not isolated to Pakistan. Thousands have sold their kidneys in the Philippines. The buyers are rich Americans, Saudis, Canadians, and Israelis who have connections and resources to travel to Manila.

Trafficking occurs in several ways. Sometimes organ donors themselves are moved from their place of residence to another country where their kidney (or, less frequently, a portion of their liver) is removed and transplanted into a waiting patient. Thus, for decades, patients from Europe and the Middle East have travelled to Turkey, and in the past decade to the former Yugoslavia, where unemployed young men from countries in southeastern Europe, such as Moldova and Romania, who had been lured with the promise of a job, become their kidney suppliers. Similar activities led to young Brazilians being the source of kidneys transplanted to foreign patients in a South African hospital in the early years of this century.

In 2004, the New York Times reported the dimension of these illegal sales. This picture describes a complexity of kidney transplantation that is been overcome by a broker system that will transport a vendor donor from Recife, Brazil to a hospital in Durban, South Africa so that a woman

from Brooklyn New York can undergo the transplant. The arrangements are done from an individual residing in Israel.

The World Health Organization has long known of these organ sales as a human rights abuse.

At the Eighth Plenary Meeting of the World Health Assembly, 22 May 2004,A57/VR/8.WHA57.18 the WHO urged Member States: (1) to implement effective national oversight of procurement, processing and transplantation of human cells, tissues and organs, including ensuring accountability for human material for transplantation; (2) to cooperate in the formulation of recommendations and guidelines to harmonize global practices in the procurement, (3) to consider setting up ethics commissions to ensure the ethics of cell, tissue and organ transplantation; (4) to extend the use of living kidney donations when possible, in addition to donations from deceased donors; and (5) to take measures to protect the poorest and vulnerable groups from transplant tourism and the sale of tissues and organs, including attention to the wider problem of international trafficking in human tissues and organs.

As a result, the international Transplantation Society (TTS) and the WHO formed a very strong alliance to combat organ trafficking and transplant tourism. As a result of worldwide consultations that were conducted by the WHO and TTS, it became evident that 10% of the organ transplants performed annually around the world were being done illicitly. The countries performing these illegal organ transplants became known to be widespread including the United States, China and India. The collaboration of WHO and TTS set out to prohibit commercial organ transplantation, to define transplant tourism and organ trafficking and place the responsibility of protecting the poor from harm and exploitation to the transplant professionals themselves.

On April 30, 2008, The Transplantation Society (TTS) and the International Society of Nephrology (ISN) convened in Istanbul, Turkey a Summit Meeting of more than 150 representatives of scientific and medical bodies, government officials, social scientists, and ethicists from around the world to take a stand on the urgent and growing problems of organ sales, transplant tourism, and trafficking in organs. The meeting adopted the "Declaration of Istanbul on Organ Trafficking and Transplant Tourism", which has since been endorsed by 130 medical societies, government bodies, and other groups involved with organ transplantation.

Organ trafficking is the recruitment, transport, transfer, harboring or receipt of living or deceased persons or their organs by means of the threat or use of force or other forms of coercion, of abduction, of fraud, of deception, of the abuse of power or of a position of vulnerability, or of the giving to, or the receiving by, a third party of payments or benefits to achieve the transfer of control over the potential donor, for the purpose of exploitation by the removal of organs for transplantation.

Transplant commercialism is a policy or practice in which an organ is treated as a commodity, including by being bought or sold or used for material gain.

Travel for transplantation is the movement of organs, donors, recipients or transplant professionals across jurisdictional borders for transplantation purposes. Travel for transplantation becomes *transplant tourism* if it involves organ trafficking and/or transplant commercialism or if the resources (organs, professionals and transplant centers) devoted to providing transplants to patients from outside a country undermine the country's ability to provide transplant services for its own population.

Principles of the Declaration of Istanbul

1. National governments, working in collaboration with international and non-governmental organizations, should develop and implement comprehensive programs for the screening, prevention and treatment of organ failure, which include:

    a. The advancement of clinical and basic science research;

    b. Effective programs, based on international guidelines, to treat and maintain patients with end-stage diseases, such as dialysis programs for renal patients, to minimize morbidity and mortality, alongside transplant programs for such diseases;

    c. Organ transplantation as the preferred treatment for organ failure for medically suitable recipients.

2. Legislation should be developed and implemented by each country or jurisdiction to govern the recovery of organs from deceased and living donors and the practice of transplantation, consistent with international standards.

    a. Policies and procedures should be developed and implemented to maximize the number of organs available for transplantation, consistent with these principles;

    b. The practice of donation and transplantation requires oversight and accountability by health authorities in each country to ensure transparency and safety;

    c. Oversight requires a national or regional registry to record deceased and living donor transplants;

d. Key components of effective programs include public education and awareness, health professional education and training, and defined responsibilities and accountabilities for all stakeholders in the national organ donation and transplant system.

3. Organs for transplantation should be equitably allocated within countries or jurisdictions to suitable recipients without regard to gender, ethnicity, religion, or social or financial status.

   a. Financial considerations or material gain of any party must not influence the application of relevant allocation rules.

4. The primary objective of transplant policies and programs should be optimal short- and long-term medical care to promote the health of both donors and recipients.

   a. Financial considerations or material gain of any party must not override primary consideration for the health and well-being of donors and recipients.

5. Jurisdictions, countries and regions should strive to achieve self-sufficiency in organ donation by providing a sufficient number of organs for residents in need from within the country or through regional cooperation.

   a. Collaboration between countries is not inconsistent with national self-sufficiency as long as the collaboration protects the vulnerable, promotes equality between donor and recipient populations, and does not violate these principles;

   b. Treatment of patients from outside the country or jurisdiction is only acceptable if it does not undermine a country's ability to provide transplant services for its own population.

6. Organ trafficking and transplant tourism violate the principles of equity, justice and respect for human dignity and should be prohibited. Because transplant commercialism targets impoverished and otherwise vulnerable donors, it leads inexorably to inequity and injustice and should be prohibited. In Resolution 44.25, the World Health Assembly called on countries to prevent the purchase and sale of human organs for transplantation.

a. Prohibitions on these practices should include a ban on all types of advertising (including electronic and print media), soliciting, or brokering for the purpose of transplant commercialism, organ trafficking, or transplant tourism.

b. Such prohibitions should also include penalties for acts – such as medically screening donors or organs, or transplanting organs – that aid, encourage, or use the products of, organ trafficking or transplant tourism.

c. Practices that induce vulnerable individuals or groups (such as illiterate and impoverished persons, undocumented immigrants, prisoners, and political or economic refugees) to become living donors are incompatible with the aim of combating organ trafficking, transplant tourism and transplant commercialism.

Although the Declaration was widely disseminated in medical journals and online beginning with a seminal article published in The Lancet on July 5, 2008. TTS and ISN were determined that the Declaration would be more than merely a statement reported in the medical literature. Therefore, in 2010, they created the Declaration of Istanbul Custodian Group (DICG) as a means of actively promoting, sustaining, and monitoring the implementation of the Declaration's principles.

To increase ethical organ donation by living related donors, the DICG encourages countries to adopt means to cover donors' financial costs, which now discourage donation. It also works with the World Health Organization to encourage ministries of health to develop deceased donation to its maximum potential, toward the goal of achieving national self-sufficiency in organ transplantation so that patients do not travel to foreign destinations to undergo organ transplantation using kidneys and partial livers purchased from poor and vulnerable people. Success in combatting human trafficking for organ removal and organ trafficking will be greatly enhanced through organizations like the DICG forging strong relationships with human rights

The precepts set forth in the "WHO Guiding Principles" (2010) align very well with the efforts of the DICG to work with countries to ensure that their laws and regulations reflect the goals of the Declaration of Istanbul. For example, WHO Guiding Principle 5 states that:

> Cells, tissues and organs should only be donated freely, without any monetary payment or other reward of monetary value. Purchasing, or offering to purchase, cells, tissues or organs for transplantation,

> or their sale by living persons or by the next of kin for deceased persons, should be banned.
>
> The prohibition on sale or purchase of cells, tissues and organs does not preclude reimbursing reasonable and verifiable expenses incurred by the donor, including loss of income, or paying the costs of recovering, processing, preserving and supplying human cells, tissues or organs for transplantation.

The firm commitment of bodies such as the WHO and the DICG to uncompensated donation has been challenged in recent years by some groups in wealthy countries, where most patients have access to treatment for end-stage organ failure and the resulting large demand for organs for transplantation is not met by the existing system of voluntary, unpaid donation. They have argued that a regulated system of financial incentives would close the gap in organ donations or, somewhat more modestly, that the long-standing prohibitions on organ purchases in laws such as the National Organ Transplant Act (NOTA), which was adopted by the US Congress with bipartisan support in 1984, should be modified to allow "pilot trials" of such incentives. The editorial board of the *New York Times* cited the work of the DICG when it rejected such a change in the law.

Instead of providing financial "benefits" to organ donors, the *Times*, like the DICG, favors removing the ancillary costs of donating – such as lost wages, travel and housing expenses to undergo donor-screening and the surgery itself – from the shoulders of organ donors. The need to pay such costs, which may average as high as $6000 is a disincentive that lowers the rate of donation, especially among people of limited means NOTA actually permits reimbursing such costs, leaving organ donation a financially neutral act, but adequate mechanisms are not in place to make sure this occurs. Potential living organ donors – and the next of kin of deceased donors – should neither be motivated by financial rewards nor deterred by financial burdens.

For the past decade, the country with the largest number of transplant tourists – and the resulting neglect of the needs of its own people – has been China, which differs from other countries where organ trafficking occurs in having relied principally on executed prisoners as the source of organs for transplantation. The procurement of organs involves a commercial transaction, but the money has gone to brokers and people in the prison system rather than to the donor. The DICG has worked diligently to persuade Chinese officials to discontinue the use of organs from executed prisoners. The number of hospitals catering to transplant tourists has been reduced and promises have been made to develop other sources of organs, but thus far it is not clear whether these efforts will fully eliminate the human rights abuses involved in relying on prisoners.

One very powerful tool used by the DICG to push Chinese colleagues to stop using organs from executed prisoners (and other transplant professionals from relying on trafficked organs) has been its ability to persuade many medical societies to disallow presentations at their congresses and publications in their journals that involve transplants derived from organ sales or from executed prisoners. Being denied the connections and the recognition that follow from visibility in such venues has led Chinese physicians and researchers to pressure their government to remove this blot on their collective professional standing internationally.

Much remains to be done to prevent human trafficking for organ removal and organ trafficking. The DICG will continue to work toward that goal, encouraged by the successes it has had, which have been widely recognized, such as by a private audience in 2014 with Pope Francis, who endorsed the principle of "financial neutrality" in organ donation. Further progress will depend not only on continued collaboration with existing partners in governments, medical institutions, and nongovernmental organizations, but on forging strong new relationships with human rights organizations and experts who are experienced in fighting all forms of illegal trafficking.

The New Alliance between Science, Policy and Religion in the Pursuit of Sustainability*

Veerabhadran Ramanathan

1. The need for the New Alliance

A series of meetings on climate change organized by the Pontifical Academy of Sciences since 2011, as well as meetings organized jointly with the Pontifical Academy of Social Sciences since 2014, have paved the way for an influential alliance between science, policy and religion. This alliance is already having a demonstrable impact on climate change dialogue by bringing the human dimension to the fore. If nurtured and developed further, the alliance has the potential for speeding up mitigation of climate change before it is too late. I am not implying that the alliance by itself can solve the climate change problem. My assertion is that it can become a transformative catalyzing agent. Currently we are at an impasse with respect to mitigating climate change. The Paris Agreement of 2015 is a breakthrough step in the path towards mitigation but it lacks verifiable and enforceable mitigation actions. Nations are struggling hard to come up with such polices but thus far have not succeeded. In the meantime, human activities are dumping about 38 billion tons of carbon dioxide every year in addition to dumping other climate warming gases and particles which amplify the CO_2 warming by a third or more. Climate change is happening now and likely to get a lot worse a lot sooner than the century timescale assumed by most people. There is still time to prevent dangerous to catastrophic climate changes. But we must act with urgency now and it is in this matter of urgency that the alliance can be of great help.

What we need, in my opinion, is massive public support and outcry for urgent mitigation actions of the sort summarized later in this text. The global reception to Pope Francis' encyclical on climate change, destined to become a classic, is a case in point. The encyclical *Laudato Si'* published in 2015 demonstrates how religious catechism is aligned with the call of scientists and policy makers to protect nature and thus protect people.

* This written version, while it retains the essential topics and ideas presented at the meeting, is a substantially expanded and modified version.

Laudato Si' is unique in its call to "…*hear both the cry of the earth and the cry of the poor*". That single poetic phrase captures the entire issue of climate justice, another topic discussed later. Religions and faith leaders have a unique authority and platform to humanize the climate change problem and highlight the ethics and morality of the actions of one billion wealthy people harming three billion poor and harming generations to be born.

By aligning with faith leaders, scientists and policy leaders can access a major potent tool in the toolkit for solving the defining problem of our day. The text will elaborate on the roles of the alliance and its accomplishments thus far. It will also make a case for how the alliance can move the dial towards a resolution to the climate change problem and thus pave the way for a sustainable planet and sustainable humanity.

2. A natural scientist grappling with a human tragedy

I would like to start with some background on how a natural scientist like me transitioned into seeking an alliance with religion. There were two singular events that catalyzed this transition. The first happened in 1975 at NASA; the second in 2014 began at the Pontifical Academy of Sciences of the Vatican and culminated in a 2-minute briefing on climate change to Pope Francis at a parking lot inside the Vatican. These two events are not singular in the absolute sense of the word, but singular with respect to the events that enabled me to recognize the force that religion can be in helping us with the climate change problem.

2.1. The delicate natural balance that maintains climate

My PhD thesis work, completed in 1973, was on the climate of Mars and Venus, both of which are an integral part of the present narrative. The atmospheres of the two planets consist primarily (96% or more) of carbon dioxide, denoted by the chemical symbol CO_2. Carbon dioxide, being the main villain of my narrative will occur repeatedly in the text and hence I will be frequently using its chemical symbol, CO_2, as a short form. The greenhouse effect of CO_2 played a dominant role in determining the super-hot temperature of Venus but it was not potent enough to prevent Mars from being frozen. The greenhouse effect is a metaphor (not an accurate one) for how CO_2 in the atmosphere warms the planet (see explanation in the box).

– Venus has too much carbon dioxide, about 150,000 times more than that of earth. As a result of the greenhouse effect of the massive amounts of CO_2 on Venus, its surface temperature is too hot at 570°C, compared with 15°C in our home planet, Earth. The common understanding is that Venus is hot because it is too close to the sun. Yes, Venus is closer to the sun than Earth and as a result receives about 90% more solar energy. Such a large amount of sunlight would have been sufficient to maintain its hot surface. However, Venus is overcast all the time with highly reflective (mirror-like) clouds. The cloud-covered planet bounces (reflects) about 70% of the incoming solar energy back to space, compared with Earth which bounces back only 29% due to its partial cloudiness. The net effect is that the solar energy entering the lower atmosphere of Venus is actually less (by 12%) than that reaching Earth's lower atmosphere and surface. The inescapable deduction is that Venus' hot climate is not due to its proximity to the sun, but instead maintained by the greenhouse effect of CO_2.

– Mars on the other hand is so far away from the sun that the solar energy reaching Mars is only 56% of the energy than that reaching Earth. The CO_2 concentration on Mars is about 23 times than that of Earth. But the larger greenhouse effect is not sufficient to overcome the significantly smaller incoming solar energy. The net result is that the surface temperature of Mars is very cold at -55°C (minus 55°C).

Thus, Earth is sandwiched between a super-hot Venus and a super-cold Mars. Earth is not only at the "right" distance from the sun but also has the "right" amount of CO_2 to be a habitable planet with water existing in all three phases: it exists as a gas (vapor) in the atmosphere bringing us weather extremes such as storms and droughts; it exists as liquid and ice in clouds bringing us rain and snow; it exists as water forming the oceans, rivers and lakes without which life as we know it would not be possible; and as ice crystals so we enjoy snowcapped mountains, ski resorts and yes, all the majestic glaciers. There were times in the past when CO_2 was elevated by 5 to 10 times the present concentration and the surface temperature was warmer by 10°C to 15°C; earth was ice-free even in the Antarctic. On Mars water can only exist mostly as ice, while on Venus it can only exist as steam, at least from the surface through the entire lower atmosphere (about 30 km thick). In summary, there are numerous supporting empirical evidences, planetary as well as paleo-climatic, for concluding that CO_2 warms the climate and its concentration in the atmosphere is a major regulator of climate of Venus and Earth.

2.2. Upsetting the delicate balance

It is the delicate balance between the distance from the sun, the CO_2 amount and cloudiness which is a major if not the dominant factor for sustaining the habitability of the planet. See the box for a brief explanation of how these three forcing factors determine climate. This balance is being disturbed drastically by human activities. The technologies that propelled the industrial revolution, relying mostly on burning fossil fuels, dumped about 2.2 trillion tons of carbon dioxide into the air since the dawn of the industrial revolution. Mr. James Watt ushered in the industrial revolution through the improved steam engine he invented in the 1770s. The greenhouse effect of CO_2 began to increase more than 150 years ago and is increasing now at alarming rates. Until 1975, scientists assumed that CO_2 was the only manmade greenhouse gas pollutant we have to worry about. There were others and these were not considered or discovered by scientists then. This brings me to the first singular event that happened to me in 1975.

2.3. The first singular event that drew me to climate change

I completed my PhD thesis in early 1974 and started looking for a job to get deeper into the climate of Venus and Mars. There simply were no jobs, either in the USA or in India, devoted to research on the climate of Mars and Venus. Looking back now, it is obvious why there were no jobs (except for a select few) in that seemingly esoteric field... but at that time it came as a rude shock to me. My only option was to rely on my Indian undergraduate engineering degree and apply for jobs in industries. Before I went to the first job interview in a tire manufacturing company, NASA out of the blue (through the intervention of a former student of my thesis advisor) offered me a job in their space vehicle reentry division. The project, unusual for a space reentry division, was to examine the Paul Crutzen hypothesis that emissions from super-sonic transport (SSTs) aircraft will deplete the ozone layer in the upper atmosphere. My specific task was to develop a climate model to evaluate how the depletion of upper atmosphere ozone will impact climate near the earth's surface. Little did I know then that in about four years I would start a life-long collaboration with Professor Paul Crutzen. It was Professor Crutzen who thirty years later, in 2004, proposed me for membership at the Pontifical Academy of Sciences (PAS). PAS, as I mentioned at the beginning, was the location of the other singular event and I will return to this PAS narrative later.

While my day time job was to evaluate the climate impacts of ozone depletion (an easy task), in the evenings I started looking at the other gases released by human activities simply out of scientific curiosity. I was very curious about their climate effects. The quantum mechanics I learned during my attempts at graduate school to model the greenhouse effects of CO_2 came in handy. It is the quantum mechanical properties of molecules that determine their climate warming effects. After about 6 months of these nighttime attempts, I stumbled on a major discovery that CO_2 was not the only manmade pollutant warming the climate but there were other greenhouse gases. This finding was published in 1975 (1). Among the non-CO_2 pollutant gases identified by me, were chlorofluorocarbons-11 and -12 (CFC-11 and CFC-12), which were used as refrigerants in refrigerators and air conditioners. They were also used as propellants in spray cans. The surprising finding was their warming potency compared with that of CO_2. A ton of CFC-11 and a ton of CFC-12 in the air had the same warming effect of more than 10,000 times of a ton of CO_2! Fortunately for the planet, CFC-11 and -12 were banned in the 1980s by the Montreal Protocol. Montreal banned CFCs not because of my climate warming findings, but due to their impact on the ozone layer. Three scientists who made pioneering discoveries of the impact of CFCs on the ozone layer received the Nobel Prize in Chemistry, two of whom, Paul Crutzen and Mario Molina, are also PAS Academicians.

So why was the large warming effect of CFCs a singular event for me personally? I was amazed at the capacity of technology and of human beings to change the environment. Even at tiny amounts of just a few parts per billion, a purely synthetic compound such as CFC-11 or CFC-12 can have such a huge impact on climate was a startling eye opener. Within two years, this discovery provided the incentive for other researchers to unearth other manmade greenhouse gases polluting the air. I knew then that the changes would be fast enough that I would live to see the predicted changes. To find out when, I teamed up with a meteorologist and predicted in 1980 that manmade climate change would become apparent (that is, the human signal will rise above the weather noise) by 2000. This was confirmed in 2001, when a team of several hundred scientists commissioned by the UN (the so-called Intergovernmental Panel on Climate Change, or IPCC), confirmed the finding of discernible human imprint on the observed temperature changes.

2.4. Coming to grips with the human tragedy

Until about 2000, the climate change problem was one of just scientific curiosity and I never thought about the human dimensions of the problem, or more appropriately, the human tragedy that could unfold with unchecked climate change. The profound importance of the climate change problem became apparent to me; in addition, the greenhouse effect of CO_2 on Venus was a constant reminder that the climate change problem could become lot worse if the pollution continued unchecked. The climate change issue began to nag me and I began to see my work not as a scientific curiosity (that brought publications in prestigious journals and honors) any more, but one that brought bad news to the world. I was finally beginning to see my papers for what they really were… obituaries for human beings likely to succumb to pollution and future climate tragedies. It was not until the encounter with Pope Saint John Paul II in 2004, that I saw a way to turn this feeling around to a more positive one. But scientific curiosity prevailed in the meantime and plenty more bad news was unearthed from research expeditions to my birth country India and the surrounding Indian Ocean. I will summarize these first before describing the singular Vatican encounter.

2.5. Climate science is data driven science

Pollution not only continued unchecked but annual emissions of pollutants were increasing rapidly. In the meantime, I followed the 1975 paper on CFCs by working with NASA engineers to design a satellite experiment to understand better the delicate balance between incoming solar radiation, cloudiness and the steadily increasing atmospheric greenhouse effect. In scientific terms, there was no more balance, but imbalance between incoming solar radiation, atmospheric greenhouse effect and cloudiness. The satellite designed to measure this imbalance was launched by NASA in 1984. Teaming up with NASA and other university scientists, I led a study which showed that clouds had a large cooling effect on the planet. In addition, analyses confirmed the massive natural greenhouse effect of water vapor; and also showed that the warmer planet could become more humid and increase the water vapor greenhouse effect feeding back and amplifying the initial warming. These findings were already inferred from climate models by numerous scientists but the observational confirmation built significant confidence in climate models.

With my students and researchers in my lab, we started collecting data from ships, surface stations and air craft including autonomous drones since 2005. More bad news about the environment was uncovered from these expeditions. The major one was the Indian Ocean Experiment conducted with 50 scientists from around the world including Paul Crutzen, Jos Lelieveld of Germany and A.P. Mitra of India. We discovered widespread 1 to 3 kilometers thick brown clouds (of air pollution particles) over south and east Asia. Follow-on studies showed the ABCs were impacting Asian climate in multiple ways: slowing down the monsoon circulation; destroying millions of tons of crops; melting glaciers and sea ice and disrupting tropical weather systems. The toxic clouds were named ABCs for Atmospheric Brown Clouds. In essence, there is a climate change problem and an air pollution problem, both of them having global as well as regional and local impacts. The discovery of climate impacts of ABCs revealed that the climate impact of air pollution was for the most part worsening the climate effects of greenhouse gases.

The basic message I am trying to convey with the above detour on observational inferences is the following: climate change science is an intense data-driven science as opposed to the dismissal by skeptics that climate change is done solely with models and hence untrustworthy. I am hoping that non-specialists, policy makers and faith leaders alike will take note of this point.

Climate System: The Delicate Balancing Act

The fundamental energy source for climate is solar energy. Not all of this energy is absorbed by the planet. The surface, the atmosphere, clouds and ice and snow cover over mountains and glaciers reflect some of the incoming energy back to space. About 29% of the solar energy is reflected back to space. The remaining 71% heats the planet and its atmosphere. In response, the surface gives off the energy as infrared (or alternately heat) radiation. But the CO_2 in the atmosphere blocks this heat radiation and radiates some back to the surface and the rest to space. The re-radiation back to surface warms the surface even more. This process goes on until what comes in as solar energy leaves the planet as heat energy and there is balance between incoming solar energy, reflected solar energy and outgoing heat energy.

The blocking of the heat energy is called as the greenhouse effect. CO_2 is not the only greenhouse gas. Water vapor, a naturally occurring gas is also a potent greenhouse gas. Clouds are the dominant regulators of climate. They reflect solar energy and cool the climate; but they also block heat energy which warms the climate.

It is the balance between incoming solar energy, reflected solar energy and outgoing heat energy that is upset by increasing the amount of CO_2. The increased CO_2 blocks more heat energy and as a result the solar energy absorbed by the planet is not balanced by the outgoing heat energy. The planet begins to warm to restore the energy balance. During this process water vapor and clouds change too and alter the amount of solar energy reflected to space as well as the heat energy radiated to space and complex set of feedback processes interferes with the balancing act.

3. A natural scientist seeking alliance with religion

3.1. Sixty years old and desolate

The year was 2004. I was in a desolate state of mind not because I was turning 60 years that November, but because of the inaction in mitigation of climate change (the 1997 Kyoto Protocol not withstanding) combined with my realization that climate change is slowly becoming a great human tragedy. The stage was set for the second singular event which began in October of 2004. I was in the Maldives islands test-flying a drone (unmanned aircraft) loaded with instruments to measure south Asian air pollution. I had envisioned this new tool (drones) to become the workhorse for monitoring climate change and air pollution and hence spearheaded an effort to develop lightweight (50 kg) drones into a viable platform. The campaign was frustrating because no one had attempted such complex measurements from small drones before and every day in the field offered a new lesson in humility. The worst lesson was the day when the drone, fully loaded with sensors and instruments, dived from about 500 feet above and crashed into the runway. About this time, an email from the Pontifical Academy of Sciences (PAS) arrived. The email had an attachment which was a letter from PAS Chancellor Monsignor Marcelo Sánchez Sorondo, announcing my election to PAS. It also mentioned Pope John Paul II. The letter informed me that the election to the Academy would happen during the first week of November. I flew to the Vatican straight from the Maldives with my island-style clothes, while the field campaign was still going on. My younger colleagues took charge happily. Nothing prepared me to what was waiting at the Vatican. Upon arrival, I purchased a dark color suit in Rome, which I still wear when attending meetings at the Vatican.

3.2. Beginning of the second singular event

I was inducted to the Academy personally by the Pope himself (now a Saint), which was a complete surprise to me. To be in the presence of the spiritual head of 1+ billion Catholics was something I never dreamt of while growing up in small towns and villages in south India. I was so glad I purchased the suit. As the Pope offered his hand to congratulate me, I took it as a blessing from the Holy Father and I had the vague feeling of witnessing a singular moment in my life. But I did not know what shape or form it would take. I had to wait for nearly 10 years, when on May 6, 2014 I gave the so-called parking lot pitch on climate change to Pope Francis outside Domus Sanctae Marthae, his residence inside the Vatican. But that singular path from Pope John Paul II to Pope Francis took me through a conference co-organized under the sponsorship of Pope Benedict XVI in 2011 with Paul Crutzen and Msgr. Sánchez Sorondo.

The conference was held from Oct 2 to 4, 2011 and was titled *Fate of Mountain Glaciers in the Anthropocene*. Voluminous data on the climate change impacts on Alps and Tibetan-Himalayan glaciers took center stage. Austrian glaciologists showed how the Alps had already lost about 75% of their mass. The Indian glaciologist showed that about 70% of small glaciers were melting. In addition, Chinese data showed that high altitudes of Tibet-Himalayas were warming twice as much as the global warming. I reported on some of the Maldivian/Indian data collected by my lab and concluded that black carbon from cook stove smoke could be contributing as much as half of the observed large warming of Tibetan-Himalayas. It was sobering to listen for three days to all of the environmental destruction. However, the main surprise of the workshop as well as the turning point for me personally, was the conference declaration. The declaration was released with a supporting conference summary of fifteen pages. Both of the documents were prepared over the next several weeks. The fifteen-page document full of technical details typical of such statements written by scientists, concluded with the following declaration:[1]

We call on all people and nations to recognize the serious and potentially irreversible impacts of global warming caused by the anthropogenic emissions of greenhouse gases and other pollutants, and by changes in forests, wetlands, grasslands, and other land uses. We appeal to all nations to develop and implement, without delay, effective and fair policies to reduce the causes and impacts of climate change on communities and ecosystems, including mountain glaciers and their watersheds, aware that we all live in the same home.

The paragraph above ended with the following call for action:

By acting now, in the spirit of common but differentiated responsibility, we accept our duty to one another and to the stewardship of a planet blessed with the gift of life. We are committed to ensuring that all inhabitants of this planet receive their daily bread, fresh air to breathe and clean water to drink, as we are aware that, if we want justice and peace, we must protect the habitat that sustains us. The believers among us ask God to grant us this wish.

[1] http://www.pas.va/content/accademia/en/events/2011/glaciers.html

As we can discern from the above, it ended with an appeal to the spiritual side of each of us without alienating the non-believers.

3.3. Formation of a science-religion alliance on climate change

The glaciers meeting declaration reproduced above was surely an unusual and atypical declaration for a predominantly scientific gathering. I have never encountered such a paragraph written by any reports such as IPCC and hundreds of other climate change reports written by scientists. But it is not atypical for a religious document. There is a huge gap between science and religion in how scientific findings are communicated to the public. Scientific facts are usually inaccessible and incomprehensible to the public; on the other-hand religious documents bring forth clearly the human dimension of the problem in such a manner that they can be understood by everyone. But religious documents on matters of science written without participation by scientists risk compromising scientific rigor and potentially misrepresenting the needed actions. And this danger can be avoided by the sort of alliance that is made possible by a prestigious science academy such as the PAS, located within the premises of the Church. The fact that the place of worship in this instance is also the Vatican, a truly historic place, helps… more so because it has a following of more than one billion worshippers from around the world with one faith leader, the Pope, to guide them. This juxtaposition of the historic Vatican and the faith leader of 1+ billion, with the Pontifical Academy of Sciences and its 80 preeminent scientists from around the world elected on scientific merit (irrespective of their nationality, race, culture and religious affiliations), turned my despair and desolateness into a profound sense of hope and optimism. My conviction then and now is that this unique combination of people and location can be a new force for the solution of the climate change problem.

I left the 2011 glaciers meeting with an understanding that the PAS-Church alliance has the potential to translate the complex scientific facts of climate change into a clear statement of the human tragedy that can be comprehended by everyone. I saw this as one avenue for transcending the current all-consuming and unproductive American debate on the reality of climate change and reach out to the public about the dangers of unchecked climate change and the urgent need to do something about it.

3.4. Sustainable Humanity, Sustainable Nature

Our Responsibility*:* Now that the human dimension of climate change can be expressed in such a bold and forthright fashion (the glaciers declaration described above), the need to bring in social scientists became apparent. An opportunity to do just that happened rather miraculously. About a year after the Glaciers meeting, I had an accidental meeting at the Vatican in May of 2013 with Professor Partha Dasgupta, an economist at Cambridge University and an Academician of the Pontifical Academy of Social Sciences (PASS). We both were attending a meeting organized by PASS. After the meeting, we bumped into each other and after half an hour of pleasantries, I found myself face to face with Partha in a restaurant not too far from the Vatican. At the end of this rather long dinner which began at 7PM and ended by about 10PM, we had developed a rather detailed plan for a joint meeting between the two academies on the general topic of sustainability of nature and sustainability of humanity. Partha proposed it next day to the Chancellor who accepted it right away very enthusiastically and asked us to start organizing it under Pope Benedict's sponsorship. PASS brought in Archbishop Minnerath from France as co-organizer, which completed the alliance between natural sciences, social sciences and religion. Archbishop Minnerath inserted the phrase "our responsibility" to the title. That was a big awakening for me since until then I had not perceived the climate change problem as my responsibility. Pope Benedict stepped down before we could organize the meeting. So the meeting was convened in May 2-6, 2014 with a message from Pope Francis. The title of the meeting was *Sustainable Humanity, Sustainable Nature: Our Responsibility*. Befitting the ambitious title and the grand setting offered by the Vatican, we managed to invite many thought leaders, including religious scholars, to conduct one of the most inter-disciplinary and broadest discussion of issues to-date. Excerpts from the long declaration are reproduced below:

Humanity has entered a new era. Our technological prowess has brought humanity to a crossroads.

Human action which is not respectful of nature becomes a boomerang for human beings that creates inequality and extends what Pope Francis has termed "the globalization of indifference" and the "economy of exclusion"... which themselves endanger solidarity with present and future generations.

The massive fossil fuel use at the heart of the global energy system deeply disrupts the Earth's climate and acidifies the world's oceans. The warming and associated extreme weather will reach unprecedented levels in our children's life times and 40% of the world's poor, who have a minimal role in generating global pollution, are likely to suffer the most.

These are matters on which all religions and individuals of goodwill can agree. These are matters that today's young people around the world will embrace, as a way to shape a better world. Our message is one of urgent warning, for the dangers of the Anthropocene are real and the injustice of globalization of indifference is serious. Yet our message is also one of hope and joy. A healthier, safer, more just, more prosperous, and sustainable world is within reach. The believers among us ask the Lord to give us all our daily bread, which is food for the body and the spirit.[2]

3.5. The parking lot pitch to Pope Francis

Before the meeting ended on May 6, Pope Francis met with the whole group of about 50 participants outside his modest residence at the Vatican. It was a parking lot. He got out of the front seat of a Ford Focus and headed straight towards us. I was completely unprepared for this encounter since my mental picture until that moment was the breathtaking hall in the Basilica where I had had my previous audiences with Pope John Paul II and Pope Benedict... Partha and I were each given two minutes to summarize the meeting. I had prepared for a 20-minute briefing, but just before meeting the Pope was told to cut it short to two minutes, due to unexpected demands on the Pope's schedule. Mercifully Partha spoke before me but I did not listen to what he said because of the mental trauma I was in, trying to reduce 20 minutes to a 2-minute summary. I summarized the meeting outcome as follows (recounting from memory and hence only approximates what I said): *Climate Change has become a serious problem and all of us assembled here are concerned; About half of the climate pollution is caused by the wealthiest one billion, while the poorest three billion who contributed less than 5% would suffer the worst consequences.* Pope Francis asked me in Spanish what he could do about it. I replied: *You as the moral leader of the world can ask people to be good stewards of the planet.*

Fifteen days later at a massive audience at the Vatican on May 22, 2014, Pope Francis reflected as follows:

The gift of knowledge helps us to avoid falling prey to excessive or incorrect attitudes. The first lies in the risk of considering ourselves masters of Creation. Creation is not a property, which we can rule over at will; or, even less, is the property of only a few: Creation is a gift, it is a wonderful gift that God has given us, so that we care for it and we use it for the benefit of all, always with great respect and gratitude.

And he urged people to nurture and safeguard Creation as God's greatest gift to

[2] http://www.casinapioiv.va/content/accademia/en/events/2014/sustainable/statement.html

us, because while God always forgives, Creation never forgives and – he warned – if we destroy Creation, in the end it will destroy us![3]

That reflection is all I needed to be reassured that the Church is solidly behind PAS as well as the science of climate change. But the real sign that the science community is ready for such an alliance came when we were asked, four months after the May 2014 Vatican meeting, to write an editorial in the prestigious American magazine *Science*. In our editorial, we emphasized the main finding of the meeting, which was: *there is a need to reorient our attitude toward nature and, thereby, toward ourselves*.[4] For the benefit of non-scientists, there are two magazines in the world, *Nature* and *Science*, where most of the major discoveries in natural sciences are published. In addition, the two journals published editorials dealing with the nexus of science-policy-society.

3.6. The momentous 2015

The year 2015 was momentous for climate change, sustainability and human wellbeing. On top of the list of events that happened that year was the release of the climate encyclical, *Laudato Si'*, by Pope Francis, followed by his US visit during which climate change was one of his main agendas. Two major summits were held on climate change at the Vatican: *The Summit of Mayors from Major Cities of the World*, and a summit with UN Secretary General Ban Ki-moon. The novel aspects of these summits was that climate change was discussed along with human trafficking, slavery and poverty, in a seamless manner. Next came the United Nations (UN) declaration of sustainable development and its 17 Sustainable Development Goals at an historic UN summit in September. The culmination of this trendsetting year was the Paris Climate Summit in December and the historic agreement that resulted. As the science advisor to the Holy See delegation for this summit, I had the front row seat to see the science-policy-religion alliance in play. Many of the developing nations, including the African Alliance, came to the Holy See delegation to champion the cause of small nations that would go underwater due to sea level rise.

[3] http://en.radiovaticana.va/news/2014/05/22/pope_francis_warns_against_the_destruction_of_creation_/1100782

[4] Dasgupta, P., and V. Ramanathan (2014), Pursuit of the common good, *Science,* 345, 1457-1458.

4. Where do we go from here?

4.1. Alliance with other religions

The fact that scientists and policy makers in academia are beginning to view this alliance with religion in a new positive light was firmly established when *Science* magazine asked us again in 2016, to reflect on the impressive developments during 2015. Monsignor Marcelo Sánchez Sorondo and I wrote the editorial in which we made an appeal: *Pope Francis' effort to unite science, policy, and religion toward an integral ecology approach is just a start. We hope that other religions and moral and political leaders will join this new synergy and nudge society toward equitable solutions to ecological and social justice problems without losing sight of the values of the human person and the common good.*

Most if not all other religions were already in a similar path as described below:

– Islamic leaders, including faith leaders, senior international development policy makers, academics and other experts, have called on the world's 1.6 billion Muslims to play an active role in combatting climate change. The leaders released *The Islamic declaration on climate change* signed in August 2015.[5]

The carefully and thoughtfully written declaration included the following call to action:

Finally, we call on all Muslims wherever they may be – Heads of state; Political leaders; Business community; UNFCCC delegates; Religious leaders; and scholars Mosque congregations; Islamic endowments (awqāf); Educators and educational institutions; Community leaders; Civil society activists; Non-governmental organizations; Communicators and media: to tackle habits, mindsets, and the root causes of climate change, environmental degradation, and the loss of biodiversity in their particular spheres of influence, following the example of the Prophet Muhammad (peace and blessings be upon him), and bring about a resolution to the challenges that now face us.

– Evangelical leaders worldwide, including over 300 leaders in the US, have been climate champions for at least a decade and have released strong statements in favor of urgent actions on climate change. Their

[5] http://www.ifees.org.uk/wp-content/uploads/2016/10/climate_declarationmMWB.pdf

declarations and call to action can be seen in the links below.[6]

- The major religions have all released strong statements in support of climate mitigation as can be seen from the website of the Yale Forum on religion and ecology. These efforts were pioneered by Professor Mary Ann Tucker of Yale University.[7]

4.2. Climate change morphing into an existential threat

Beginning in 2010, along with my students and young researchers under my mentorship, I went back to the satellite/ship/aircraft/surface data collected during the past thirty years with a single question: What is the worst possible outcome of unchecked emissions of climate-warming pollutants? My hope in asking this question was that the data would reassure us that the change would not be catastrophic. Instead, the data-driven analyses informed us that there is a small chance (5% probability, i.e., a chance of 1 in 20) the warming by end of the century could be in the 4°C to 6°C range, taking us back to the ice-free hot climates of 30 million years ago. Simultaneously, paleontologists and ecologists including PAS and PASS Academicians such as Profs. Peter Raven and Partha Dasgupta, were informing us that the stage was being set for mass extinction due to habitat destruction and land use alterations. Climate change in excess of 4°C could commit 20% or more of known species to extinction. Simultaneously epidemiologists and meteorologists were concluding that a 4°C warming could expose more than 75% of the population to deadly heat. These independent studies along with our analyses led my student Professor Yangyang Xu and myself to conclude that climate change resulting from unchecked emissions of pollution would pose existential threat to all of humanity.

4.3. Can we solve the problem in time?

The answer to this question is a definite and unqualified Yes. Solutions have been published in numerous documents by many international groups and publications. Any solution has to take the following projections into account:

- The planetary warming will reach 1.5°C by 2030; The last time the planet was about 1°C to 1.5°C warm was 130,000 years ago and the

[6] http://www.christiansandclimate.org/; https://www.lausanne.org/content/ctc/ctcommitment.

[7] http://fore.yale.edu/climate-change/statements-from-world-religions/

sea level rose by 5 to 7 meters. The planet is already warmer by 1°C compared with pre-industrial temperatures.
- If the current rate of emissions continues past 2030, the warming will reach 2°C by 2050. Most scientists consider 2°C as the threshold for dangerous climate warming. Some argue that even 1.5°C is dangerous.
- If the current rate of emissions continues beyond 2050, the warming has a 50% probability of reaching 4°C before the end of the century. It has a 5% probability of reaching 6°C. Warming in the range of 4°C to 6°C will pose existential threats to all people, young and old as well as poor and rich.

There are two separate but related issues: the warming reaching dangerous levels within the next 12 to 32 years (from 2018). This is the near-term problem. Next is the warming posing catastrophic to existential risks some time during 2050 to 2100. This is the longer-term problem.

The first step towards a solution is to recognize that fossil fuels have become an outdated energy source. Fossil fuels should also be recognized as hazardous in view of the health impacts of fossil fuel-related air pollution and climate change. There are other environmentally safer energy sources and that too in abundance. In order to protect people and the planet from both the near-term and longer-term threats, we need to pull on the following three levers:
- *Carbon Lever*: We have to achieve carbon neutrality by 2050. Carbon neutrality is scientific jargon for zero emissions of carbon dioxide. Carbon dioxide currently contributes 50% to 60% of the warming and will become the dominant source of warming beyond 2050. This is a complex matter and involves global energy use and energy access, industrial processes, agriculture, transportation and others. There are scalable technological solutions to achieve about half to 2/3 of the required reductions; and for the remaining 1/3 to half, promising new technologies are being developed. Simply stated, carbon neutrality can be achieved by converting all end uses, including transportation to electricity, and generating that electricity using renewable sources such as solar, wind, geothermal and hydro power. Electricity can be stored in batteries. It can also be stored in hydrogen, provided hydrogen is produced using solar power and water. The stored hydrogen can be burned using fuel cells. For those applications for which electricity is not a viable option (e.g. air transportation), transportable fuels can be produced (e.g. jet fuel) using algal sources. These climate mitigation steps are already well under way. More than 8 million people are employed in the renewable

industry: more than half of the new energy during the past few years was generated through solar and wind. About 55 cities and 62 major industries have already put in place climate mitigation plans to reduce their carbon emissions by more than half by 2040.

– *Short-Lived Climate Pollutants Lever*: There are four other climate warming pollutants which currently contribute 40% to the warming: Methane; Black Carbon; Ozone & Hydrofluorocarbons (HFCs). Methane, ozone and HFCs are greenhouse gases; while black carbon is a particle and warms the climate by trapping solar radiation in the air. Their lifetimes are much shorter (1 week to about 12 years) compared with the 100 to 1000 years lifetime of carbon dioxide, and hence their warming effect will decrease quickly in response to mitigation actions. There are also many technologies off-the-shelf that can be deployed on large scales. California has already passed laws to drastically reduce their emissions. The United Nations Environment Program has already created a Climate and Clean Air Coalition with 80 member countries to mitigate the emissions of short-lived climate pollutants. In addition, the Montreal Protocol ratified by almost all nations, was amended in 2016 to include the phase-out of HFCs. If available mitigation technologies are implemented globally beginning in 2020, the projected warming from now until 2050 can be cut by half. Thus, this lever can prevent the warming from exceeding 2°C in the near-term.
– *Atmospheric Carbon Extraction (ACE) Lever*: Pulling on the two levers above as hard as possible beginning 2020 (that is in two years) would be able to keep the warming below 2°C with about 50% probability. A 10-year likely delay would necessitate pulling on the third lever, which would remove the carbon dioxide that is already up there. A 10-year delay would require us to take out as much as one trillion tons of carbon dioxide before 2100. One trillion is: 1000 x 1000 x 1000 x 1000. That is a huge amount of carbon that has to be taken out. There are no scalable technologies or measures to pull on this lever now, but various promising measures are being explored. These include: afforestation; soil restoration to increase its ability to store carbon for centuries or more; chemically removing CO_2 and finding industrial use for the removed carbon; enhance ocean fertilization; produce bioenergy sustainably and sequester the carbon in natural reservoirs; and others. We have to accelerate efforts to develop scalable methods for this lever to be cost effective.

While the solutions above are feasible in principle, implementation would require behavioral changes, global to local governance, market mechanisms, technology development, forest and soil management. Above all societal transformation is required to create massive public support for implementing the solutions with urgency. Alliance with religion could be a major factor in effecting transformational changes in public support.

6. The role of the science-policy-religion alliance

First, places of worship usually offer a politically neutral forum to reach out to the public about climate change. Such a measure, would help offset the crippling politicization of climate change.

Second, behavioral change is essential to achieve carbon neutrality, and faith leaders have more authority than scientists to appeal for behavioral changes directly to the public. The needed behavioral changes include: i) avoiding wastage of food. A third of the produced food is thrown away and avoiding this waste could reduce CO_2 emissions by billion tons or more a year; ii) energy and natural resources are also wasted and these wastage should be avoided; iii) in many regions it is already cost-effective and economical to switch to renewables and in such locations the public can be urged to switch; iv) As much as possible rely on plant based diets for they are less carbon intensive and also healthy; v) educate family, friends and fellow citizens about the climate urgency and the available solutions; vi) Urge people to support governmental measures to protect the poor and vulnerable from extreme climate events such as droughts, fires, floods and sea level rise.

Third, places of worship offer a unique forum to bring up ethical and moral issues of climate change. Melting of glaciers and sea level rise will last centuries to thousands of years and hence generations of children and grandchildren yet to be born will suffer because of our unsustainable actions today.

Fourth, faith leaders have the moral authority to establish clearly the equivalence between protecting creation and protecting the poor; protecting nature and protecting all species.

Last, climate mitigation actions taken by religious institutions within their jurisdictions will serve as a huge role model and living laboratory for others to follow.

7. Returning to Mars, Venus and the sandwiched planet Earth

There is a fundamental planetary quantity called Albedo. Albedo is the percent of sunlight reflected back to space by a planet. Venus reflects 70% of the incident sunlight. So, albedo of Venus is 70%. Earth's albedo is 29%

and Mars' albedo is 15%. Why is Venus' albedo so high or more colloquially, why is Venus so bright? Because it is completely cloud covered, that is, its cloud cover is 100%. Earth in the absence of clouds will reflect only about 14%. I know this because I measured it from the satellite experiment I designed with NASA in late 1970s. Clouds on Earth, although only partially filling the sky except during rainy days, double the albedo from 14% to 29%. With that background, let me conclude with my nightmare about climate change. If, due to climate change the earth's albedo decreased slightly to 27% (instead of 29%) it would be hotter by about another 5°C, beyond the 4°C warming predicted by 2100. Many studies predict that sea ice would eventually disappear if the warming continues. This single process alone, when it happens, would decrease the albedo from 29% to 28.5%. It is not inconceivable that if the planet is allowed to warm to 4°C, cloudiness can shrink (due to the heat) and decrease the albedo by another 1.5% to 27%. Climate models may claim this is not probable. But, do we want to risk our entire future to reassurance by climate models?

Solutions are available. Because of the trillions of dollars cost of the impact of fossil fuels on human health and on the ecosystem, we must choose the safer as well as cost-effective option and begin mitigation actions immediately. My claim is that alliance with faith leaders can help guide people towards that safer option.

References

Since this article is largely a biographical exposition, it relies mainly on author's papers. There is no claim on the part of the author that the references below are the only major papers on the topic of the paper.

1. Ramanathan, V. and R.D. Cess, 1974: Radiative Transfer within the Mesospheres of Mars and Venus. *Astrophysical J.*, 188: 407-416.
2. Ramanathan, V., 1975: Greenhouse Effect Due to Chlorofluorocarbons: Climatic Implications. *Science*, 190: 50-52.
3. Madden, R.A. and V. Ramanathan, 1980: Detecting Climate Change Due to Increasing CO2 in the Atmosphere. *Science*, 209: 763-768.
4. Ramanathan, V., R.D. Cess, E.F. Harrison, P. Minnis, B.R. Barkstrom, E. Ahmad, and D. Hartmann, 1989: Cloud-Radiative Forcing and Climate: Results from the Earth Radiation Budget Experiment. *Science*, 243: 57-63.
5. Raval, A. and V. Ramanathan, 1989: Observational Determination of the Greenhouse Effect. *Nature*, 342: 758-761.
6. Ramanathan, V., P.J. Crutzen, J. Lelieveld, A.P. Mitra and 20 authors (2001). The Indian Ocean Experiment: An Integrated Assessment of the Climate Forcing and Effects of the Great Indo-Asian Haze. *J. Geophys. Res. Atmospheres*, 106, (D 22), 28371-28399.
7. Ramanathan V., M.V. Ramana, G. Rob-

erts, D. Kim, C.E. Corrigan, C.E. Chung & D. Winker (2007). Warming trends in Asia amplified by brown cloud solar absorption. *Nature,* 448, 575-578 doi:10.1038/nature06019.
8. Xu, Y. and V. Ramanathan, Well below 2°C: Mitigation strategies for avoiding dangerous to catastrophic climate changes. Proceedings of the National Academy of Sciences, early online edition, Sept 14, 2017.

SPECIAL SESSION

Energy

(Theodor W. Hänsch)

Introduction to the Special Session on Energy

Theodor W. Hänsch

Without energy, there could be no life and no human civilization. With the world's growing population and increasing industrialization, the consumption of energy is rapidly reaching levels that cannot be sustained. The competition for energy has become a central issue of politics, war and peace. Moreover, by continuing to burn fossil fuels, we add to the green house gases in the atmosphere and endanger the earth's climate, long before the finite fuel supply is exhausted. We have been warned repeatedly of the perils of climate by experts in our academy.

What can we do for a sustainable future? How and to what extend can modern science and technology create new options? Can one perhaps use the energy stored in fossil fuels without increasing the CO_2 concentration in the atmosphere? What about nuclear power? Are there ways to produce nuclear fission energy without the risks of accidents or long-lived nuclear waste? Fusion energy has long promised an unlimited supply of clean energy. Is it technically and economically feasible to tame here on earth the fusion reactions that power the sun? Can renewable energies such as solar power or wind power make a difference? How can we deal with the large temporal fluctuations of such energy sources? What are the future prospects for better electrical batteries? What other options can we recognize? How much energy are we wasting in industrialized countries. How much could we save?

To stimulate discussions about such questions, I have been asked to organize this special session on energy. The members of our Pontifical Academy Carlo Rubbia, Klaus von Klitzing, and William Phillips have kindly offered to contribute. They will be joined by four guest speakers, Stephen Chu, Jean-Pierre Revol, Sibylle Günter, and Yi Cui, some of the world's leading experts on energy. We are grateful that they have agreed to come to Vatican City and share their insights at this Plenary Session of the Pontifical Academy.

The session will be opened by an overview given by Professor Stephen Chu, presently Professor at Stanford University, 1997 Nobel Laureate in Physics, and Secretary of Energy of the United States in the cabinet of

Barak Obama from January 2009 to April 2013. Perhaps no one else has a broader or more insightful view of the issues involved.

Carlo Rubbia will give us his vision on the future of energy. Professor Rubbia is proposing novel methods of transporting energy from renewable sources over long distances and new ways to achieve a large reduction of CO_2 emission in the burning of fossil fuels.

Guest speaker Dr. Jean-Pierre Revol from CERN will present his proposal for sustainable Thorium fission energy.

Guest speaker Professor Sybille Günter will talk about the prospects of fusion energy. Dr, Günter is managing Director of the German Max-Planck-Institute of Plasma Physics, the largest research institute of the Max-Planck Society with large laboratories in Garching and Greifswald devoted to the exploration of fusion energy.

Klaus von Klitzing, an expert in condensed matter physics, will speak about the future of solar cells and solar energy.

Guest speaker Professor Yi Cui, Stanford University, is an innovator and expert on novel nano-materials and perhaps the world's most highly cited researcher in his field. He will present his vision for energy storage in novel batteries.

Finally, Bill Phillips will discuss new ways of conserving energy or of using energy more efficiently

The session will conclude with a general discussion.

Short biographies of the guest speakers

Professor Steven Chu, *Stanford University*

Steven Chu is the William R. Kenan, Jr., Professor of Physics and Professor of Molecular & Cellular Physiology in the Medical School at Stanford University. He has published 260 papers in atomic and polymer physics, biophysics, biology, biomedicine, batteries, and holds 10 patents.

Dr. Chu was the 12th U.S. Secretary of Energy from January 2009 until the end of April 2013. As the first scientist to hold a Cabinet position and the longest serving Energy Secretary, he recruited outstanding scientists and engineers into the Department of Energy. He began several initiatives including ARPA-E (Advanced Research Projects Agency – Energy), the Energy Innovation Hubs, the U.S. – China Clean Energy Research Centers (CERC), and was tasked by President Obama to assist BP in stopping the Deepwater Horizon oil leak. Prior to his cabinet post, he was director of the Lawrence Berkeley National Laboratory and Professor of Physics and Molecular and Cell Biology at UC Berkeley. Previously he was the Theodore and Francis Geballe Professor of Physics and Applied Physics at Stanford University, and head of the Quantum Electronics Research Department at AT&T Bell Laboratories.

Dr. Chu has numerous awards including the 1997 Nobel Prize in Physics for the laser cooling and atom trapping, shared with Claude Cohen-Tannoudji and William Phillips. He holds 26 honorary degrees and is a member of the National Academy of Sciences, the American Philosophical Society, the American Academy of Arts and Sciences, the Academia Sinica, and is a foreign member of the Royal Society, the Royal Academy of Engineering, the Chinese Academy of Sciences, and the Korean Academy of Sciences and Technology.

Professor Jean-Pierre Charles Revol, *CERN*

Jean Pierre Charles Revol obtained his PhD degree at the MIT Physics Department in 1982. After a three year fellowship at CERN, he became a faculty member of the MIT Physics Department from 1984 to 1981. In 1991, he joined CERN to become adviser to the Director General of CERN (Prof. Carlo Rubbia). He has contributed to many important experiments at CERN in leading roles.

In 2012, Jean-Pierre Revol was one of the founding members of the international Thorium Energy Committee (iThEC), and became its first president. iThEC is an international, not for profit association in Geneva, Switzerland, which gathers, physicists, engineers, local politicians, and individuals concerned with the energy problem, with the common goal of promoting energy R&D on thorium.

Professor Sibylle Günter, *Max-Planck Institute of Plasma Physics (IPP)*

Sibylle Günter is the Scientific Director of the Max-Planck Institute of Plasmaphysics, the largest research institute within the German Max-Planck-Society. She was born in Rostock, Germany, and studied Theoretical Physics at the University of Rostock where she completed her PhD with a thesis on computational investigation of radiation from dense plasmas in 1990. From 1990 till 1996 she served as Scientific Assistant with the Chair of Theoretical Physics I. Her studies at the University of Rostock were extended by stays at the University of Maryland and as visiting scientist at the National Institute of Standards and Technology (NIST). She qualified for lectureship in 1996 with a thesis entitled „Optical Properties of Dense Plasmas“ at the University of Rostock, where she still gives lectures.

Since February of the same year she has been a member of staff at Max-Planck-Instiute for Plasma Physics. On 1 July 2000 she was appointed Head of the Tokamak Physics Division (till 2011). Since 2001 she is adjunct professor at Rostock University, since 2006 „Honorarprofessor“ (part-time professor) at the Technical University of Munich. Since February 2011 she is the Scientific Director of IPP.

Professor Yi Cui, *Stanford University*

Yi Cui is Professor at the Department of Materials Science and Engineering at Stanford University. From 1993 to 1998, he studied Chemistry at the University of Science and Technology of China (USTC). Afterwards, he moved to the US, and he obtained his PhD degree in Chemistry at Harvard University in 2002. After spending three years as a Miller Postdoctoral Fellow at UC Berkeley, he joined the faculty of the Stanford Department of Materials Science and Engineering in 2005. He was promoted to Associate Professor in 2010, and he became a Full Professor in 2016.

Cui studies nanoscale phenomena and their applications. His research interests cover the synthesis and self-assembly of nanocrystal and nanowires, electron transfer and transport in nanomaterials and at the nanointerface, nanoscale electronic and photonic devices, batteries, solar cells, microbial fuel cells, water filters and chemical and biological sensors.

On the Future of Energy: The De-Carbonisation of Methane

Carlo Rubbia

As is well known, we are presently facing a novel phenomenon, coined by Eugene Stoermer and popularized by the Nobel Laureate Paul Crutzen, namely the emergence of a manmade Anthropogenic Era. For the first time, human activities may strongly influence the future of the earth's climate. The development of low-carbon techniques to produce hydrogen from fossils could be of great importance during the transition to a long-term sustainable energy system.

In this framework, at the Institute for Advanced Sustainability Studies (IASS) in Potsdam, a new alternative technology for methane decarbonisation based on liquid metal technology has been proposed. An ambitious programme was set up in collaboration with the Karlsruhe Institute of Technology (KIT) and carried out successfully over a period of three years. The project was awarded the Innovation Prize of the German Gas Industry Association in Berlin in December 2018. Future CO_2-free Methane de-carbonisation based on liquid metal technology may become a further development of our experimental activities in China and elsewhere.

In this paper we discuss natural gas utilisation options in view of reducing CO_2 emissions. Three methods (Figure 1) are here compared: (a) conventional process with CO_2 emitted in the atmosphere; (b) geo-engineering attempts to compensate for CO_2 emissions; and (c) methane cracking without CO_2 emissions.

Since 1750 about one million million tons, 1000 Gtons, of CO_2 have been injected into the atmosphere. From about 6 GtC/y in the early nineties, we are now at 9.5 GtC/y. By 2020 and at the present rate of increase, the CO_2 will reach twice the 1990 rate $\approx$ 12 GtC, a factor 2 over 30 years.

The average lifetime of large amounts of anthropogenic CO_2 is $\approx$ 30 kyr. As a comparison, the nuclear lifetime of Plutonium (Pu-239) is 26 kyr. The surviving fossil carbon will be of about 10-15% after 10,000 years and about 7% after 100,000 years: in practice it will last forever. At such rates, it is indeed urgent for emissions not be freely emitted indefinitely and some future CO_2 curbing mechanism is unavoidable.

Geo-engineering technologies may be used in order to provide for CO_2 mitigation. But, as noted by the Royal Society (2009), the safest and

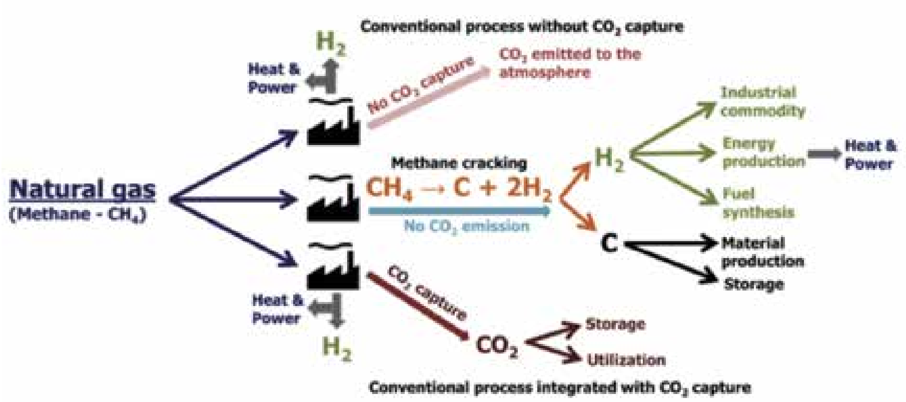


Figure 1. Natural gas-driven conventional processes: (a, top) without CO_2 capture, (b, bottom) processes integrated with CO_2 capture and (c, middle) methane cracking process without CO_2emissions.

most predictable method of moderating climate change is to take early and effective action to reduce greenhouse gas emissions. No geo-engineering method can provide an easy or readily acceptable alternative solution to the problem of climate change. Geo-engineering methods could however potentially be useful in the future to augment continuing efforts to mitigate climate change by reducing emissions and thus should be subject to more detailed research and analysis.

Underground storage of CO_2 was initially studied by Herzog *et al.* [1]. Carbon capture and sequestration (CCS) is seriously being considered: the CO_2 is injected down into the earth or ocean bottom. This method is already used by the oil industry, but at the level of few million tons/y. Several billion US$ have already been spent by the USA, and similar incentives have been given elsewhere. However, CCS is not applicable to all sources of CO_2.

Sequestration is not elimination, and eventually CO_2 will have to come back into the atmosphere, after dissipation of the greenhouse effect and after thousands of years of accumulation!

Safety considerations are especially important. The degradation processes of the sealed wells and their behaviour over a long timeframe (millennia) are difficult to predict. Provided the likelihood of leaks from a CO_2 reservoir is similar to that of hydrocarbon reservoirs during production, leaks (> 10 t/day) are expected to occur at about 10-3 per reservoir x year. But we need CO_2 wells under pressure for >103 years and therefore accidental leaks are frequent. The expanded CO_2, if promptly emitted, will be very cold and hence remain close to the surface of the escaping area.

Although not toxic, above some % CO_2 acts as a powerful brain vein dilatator. In a few minutes, unconsciousness occurs at 15% of relative concentration and immediate death at 30%. Deaths start being observed already at 9%. In 1986 at Lake Nyos a volcanic CO_2 leak of 2.4 x 105 ton killed all the 1746 people + animals < 15 km from the source.

In order to ensure 550 ppm by 2100 with the option "Business as usual" – according to IPCC – we must accumulate CSS with ≈ 2 x 1012 ton.

Another alternative may be Aerosol SO_2 cooling. If there were a way to continuously inject SO_2 into the lower stratosphere at a level of ≈ 1/1000 of the CO_2 emissions, it would produce large, compensatory global cooling.

Worldwide SO_2 emissions have increased from about 10 million tons of Sulfur per year (Mt S/y) to a peak of 65-70 Mt S/y in the early 1980s and have been declining to about 55 Mt S/y as of 2000. The main advantage of these non-CO_2 effects is that the weight of the material to be captured is of the order of millions of tons, and not billions of tons as in the case of CO_2.

Let us assume that we will put SO_2 into the lower stratosphere (16-22 km) over the Equator at a daily rate equal to 5 Mt/yr (1 Pinatubo eruption

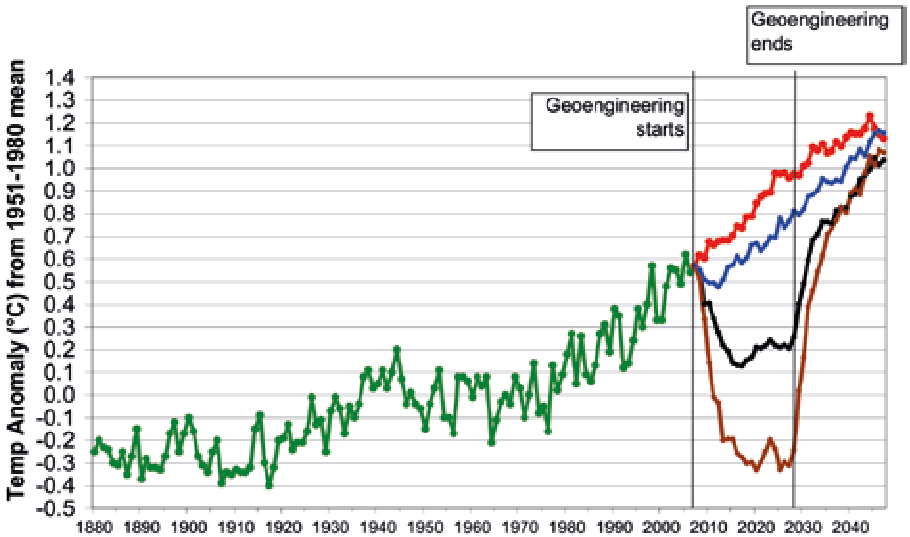


Figure 2. At the end of SO_2 injection period, CO_2-caused effects will promptly return.

every 4 years) or 10 Mt/yr (1 Pinatubo every 2 years) for 20 years, or at 68°N at a daily rate equal to 3 Mt/yr for 20 years (Figure 2).

Volcanic eruptions inject mostly SO_2 but it is preferable to produce H_2S that would oxidize and form H_2SO_4 droplets with water. However, H_2S is toxic and flammable. Using airplanes would not be costly, especially with existing military planes, but there are still questions about whether desirable aerosols could be created. No means have been studied so far on how to inject aerosol precursors (gases). Rough estimates show it would cost a few billion dollars to build a system, a few billion dollars per year to operate it and less than a decade to implement.

However, eventual schemes perceived to work will lessen the incentives to mitigate greenhouse gas emissions. Even if it works, whose hand will be on the thermostat? How could the world agree on an optimal climate? Who has the moral right to advertently modify the global climate?

In the past 2000 years there have been three major high altitude natural eruptions: Eldgjá, Iceland in the year 939, Lakagígar (Laki), Iceland (14.7 km3 of lava) in the years 1783-84 and Novarupta (Katmai), Alaska in the year 1912.

Quoting Reference [3] the 1783 flood was not sufficient in Egypt. The Nile failed to rise again in 1784 and the death toll was very high. The famine continued, and the streets of Cairo, previously full of beggars, were now deserted: all had perished or escaped from the city. By January 1785, 1/6 of the population of Egypt had either died or left the country.

The beginning of the French revolution was also strongly influenced by the famine related to the Laki eruption. Famine devastated India as the monsoon failed in summer 1783. There was also the Great Famine in Japan in 1783-1787, which was exacerbated locally by the Mount Asama eruption of 1783.

Returning to the present, we have suggested using a new procedure, fossil Methane de-carburation. Methane cracking or Methane de-carburation is a proven process based on the splitting of the Methane molecule into its atomic components, Carbon and Hydrogen. As an alternative without CO_2 emissions we have investigated the experimental feasibility aspects of *the spontaneous, thermal dissociation of NG*:

$$CH_4 \rightarrow 2H_2 + C$$

Hydrogen becomes the final form of energy. The total absence of CO_2 is the main reason for its development. The black carbon produced can either be sequestered or sold on the market as a material commodity, for instance reducing costs by marketing the carbon as a filler or construction material.

At IASS-KIT we have evaluated and carried out at laboratory scale this novel methane decarbonisation process, successfully overcoming the obstacles, in view of its possible industrial implementation. The preferred option, in analogy with most of the previous studies, is based on molten metals, as carbon separation seems more achievable due to the large density difference between the liquid metal and the carbon.

As early as 1930, Tyrer had proposed and patented a process for producing hydrogen from methane or methane-containing gases using molten iron (1200-1300°C). Many authors have pursued the technology since then.

In our opinion, a future progressive industrialization of molten media to host the methane-cracking reactions is promising, although a major change is required because of the large amounts of black carbon produced.

The present (table top) project we have completed is based on the implementation of a *liquid metal technology* for the production of H_2 from NG without CO_2 emissions. The main features have been the following: bubble formation in ceramic sponges and a liquid metal bath; compatible liquid metals, such as Lead or Tin; high temperatures (approximately 1200°C); and compatible with Hydrogen production (Figure 4).

A crucial choice is the possible presence of catalysts in the reaction. Significant effort had been previously devoted to providing catalysts to the

Figure 3. Carbon powder accumulated on the surface of the liquid metal along with quartz glass pieces that formed the packed bed.

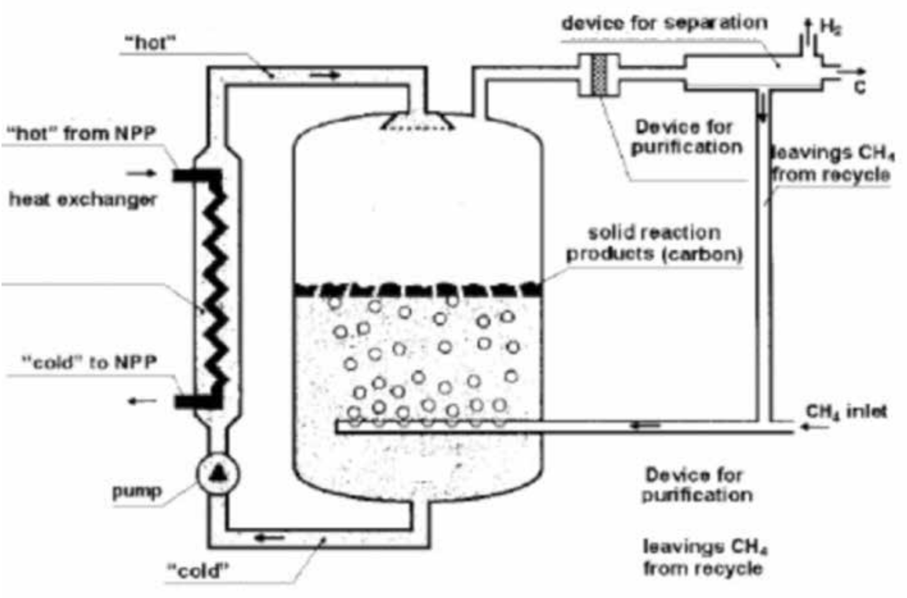


Figure 4. Early decomposition through bubbling of NG through a molten metal at high temperature. Small bubbles enhance the NG to hydrogen conversion.

reaction in order to achieve a viable implementation also below 1000°C. The industrial implementation in the case of catalysed reactions is limited by the deactivation of the catalyst and by its lifetime and cost.The deactivation of the catalyst is a process f.i. resulting from the formation of coke on the surface of the catalyst during its operation. Solutions with no catalyst are hereby preferred (Figure 3).

Several aspects have been carefully analysed: the formation of Carbides or Hydrides in liquid metal; the removal of Carbon plugging of the structural materials; separation of pure H_2 from the remaining hydrocarbons and carbon; and recovery of Carbon particles from the liquid metal.

Process	Methane steam reforming	Coal gasification	Methane pyrolysis
Reaction	$CH_4 + 2H_2O = CO_2 + 4H_2$	$C + 2H_2O = CO_2 + 2H_2$	$CH_4 = C + 2H_2$
Heat of reaction (kJ/mol-H_2)	63.25	89.08	37.43
Energy efficiency in transformation (%)	74	60	55
Energy efficiency with CCS (%)	54	43	55
CO_2 emission (mol-CO_2/mol-H_2)	0.34	0.83	0.05
Carbon production (mol-C/mol-H_2)	0	0	0.5

Methane pyrolysis can be compared to the standard *Methane Steam reforming* MSR. Industrial Hydrogen generation is now 1.9 x 1011 Nm_3/y, ≈ 5% of the Oil production (84 MBOL/d). MSR is producing commercial H_2 with CO_2 starting from NG with 700-1100°C and efficiencies of 70-80%.

Hydrogen yields have been studied as a function of temperature at 50 mln/min and 200 mln/min (Figure 5) pure methane volume flow rate for two different packed bed designs: cylindrical rings (porosity 84 vol-%) from the current study and quartz glass fragments (porosity 76 vol-%) published earlier in Geißler *et al.* and *equilibrium hydrogen yields* as a function of temperature at 1 bar, 1.5 bar and 2 bar (dashed lines).

The technical feasibility of methane decomposition in a liquid metal bubble column reactor has been successfully demonstrated (Figures 6 and 7). The maximum hydrogen yield of 78% was obtained at 1175°C. No major differences in terms of hydrogen yield were found between experiments.

Diluting the methane feed gas with nitrogen in the range of 0-90 vol-%, revealed no significant influence on the resulting hydrogen yield in the investigated temperature range.

During the present experiments, no clogging issues due to solid carbon deposition on reactor walls or other parts occurred. The produced carbon mainly accumulated above the liquid metal interface in powder form with particle sizes in the range of 15-20 µm.

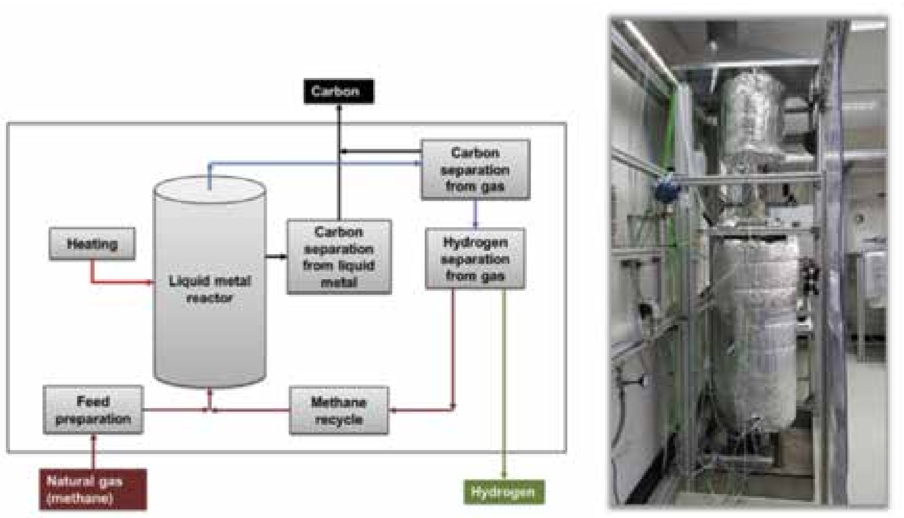


Figure 5. (a) Basic definition of the methane de-carbonisation process; (b) photograph of the methane cracking facility at KIT showing the insulated liquid metal reactor in the bottom.

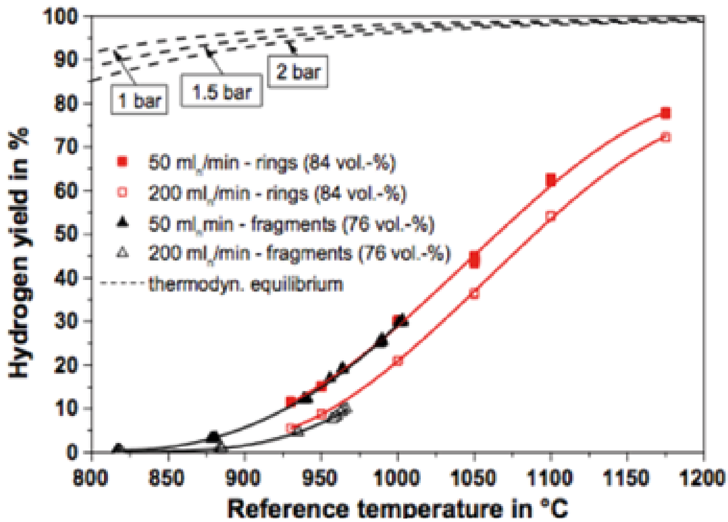


Figure 6. Hydrogen yields as a function of temperature.

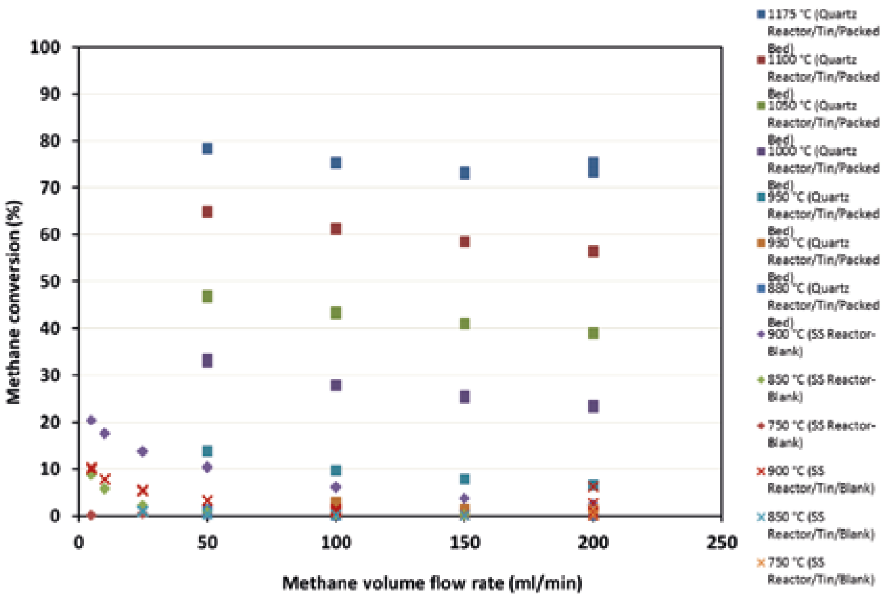


Figure 7. Experimental fraction of NG to Hydrogen conversion. Useful data cover the temperature interval from 1000°C to 1175°C.

Disassembling the reactor after 15 days of operation, only a thin carbon layer, around 10 μm in thickness, was found.

The present production of black carbon is ≈ 6 million tons/y. The industrialisation of the NG de-carbonisation is considering the additional accumulation of much larger amounts of black carbon.

$$\underset{CH_4}{890\,kJ/mol} + \underset{\Delta heat}{76kJ} \rightarrow \underset{Black\ C}{394\,kJ/mol} + \underset{2\times H_2}{572\,kJ/2mol}$$

The direct combustion of NG will produce 890 kJ/mol. Instead, the combustion of the resulting H2 is 572.2 kJ/2mol H2. The product's theoretical efficiency is then 64%. Black carbon represents 394 kJ/mol C. Its final mass is 75%.

The endothermic contribution of the transformation in Black C and $2H_2$ is 76 kJ/CH_4 mol, i.e. 8.5% of the CH_4. This contribution may be produced with additional CH_4 and a small CO_2 contribution or from H2 with some reduction in efficiency.

However, Hydrogen is a gas and its transformation into a general-purpose final product is extremely expensive: there is need for a liquid fuel: methanol has been chosen.

Methanol freezes at -97.6°C, boils at 64.6°C, and has a density of 0.791 at 20°C. It is a convenient, safe liquid easily obtained from existing coal or natural gas sources via classic methods developed and practiced since the 1920s. Roughly 8% of the fuel used in the Chinese transportation system is methanol. China is now the largest producer of methanol in the world.

Methanol can also be readily converted into many other chemicals like ethylene, propylene and others. Methanol not only represents a convenient, safe way to store and transport energy, but together with its derived product dimethyl ether (DME), is an excellent fuel.

Therefore it could replace oil both as a fuel and chemical raw material, mitigating the dangers of global warming without costly new infrastructures.

Let us assume that we recover CO_2 as a chemical material (Figure 8), recycling it from a conventional source of concentrated CO_2 waste, removed by the recovery of the CO_2 conversion of the previous application (two for one). We can combine it with Hydrogen, for instance produced with black carbon, and without CO_2 from the de-carburation of NG.

CO_2 and hydrogen can produce Methanol and water, a liquid substitute of Gasoline in all distant transport applications.

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \qquad CH_3OH + 3/2O_2 \rightarrow CO_2 + 2H_2O$$

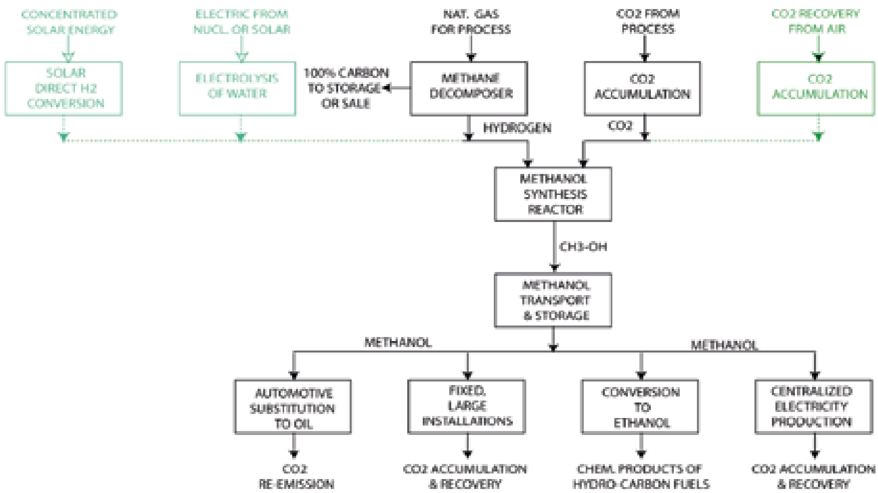


Figure 8. Transforming CO_2 from a liability to an asset.

If Methanol or its substitute were burnt in a concentrated source, its CO_2 could be indefinitely recycled. Otherwise CO_2 may be re-emitted, returning it to the atmosphere.

Finally, we should be aware that an important new development is expanding the availability of NG. In 2000 Shale gas provided only 1% of U.S. natural gas production; by 2010 it was over 20% and the U.S. government predicts that by 2035 46% of the United States' natural gas supply will come from shale gas.

Methane hydrate (the so-called *Burning Ice*) is the most abundant natural form of clathrate, a chemical substance in which molecules of water form an open solid lattice that encloses, without chemical bonding, appropriately-sized molecules of methane (Figure 9).

Future supply options (Figure 8) are nuclear and solar energies for Hydrogen and the capture from the atmosphere for CO_2. At high pressure methane clathrates remain stable up to 18°C. One litre of methane clathrate contains as much as 168 litres of methane gas.

According to either of the above methods, the NG from the bottom of the ocean or permafrost can be directly extracted liberating the clathrates and bringing them to the surface. The methane hydrates in sediments in part of U.S. territory alone could supply the present U.S. natural gas needs for > 103 years.

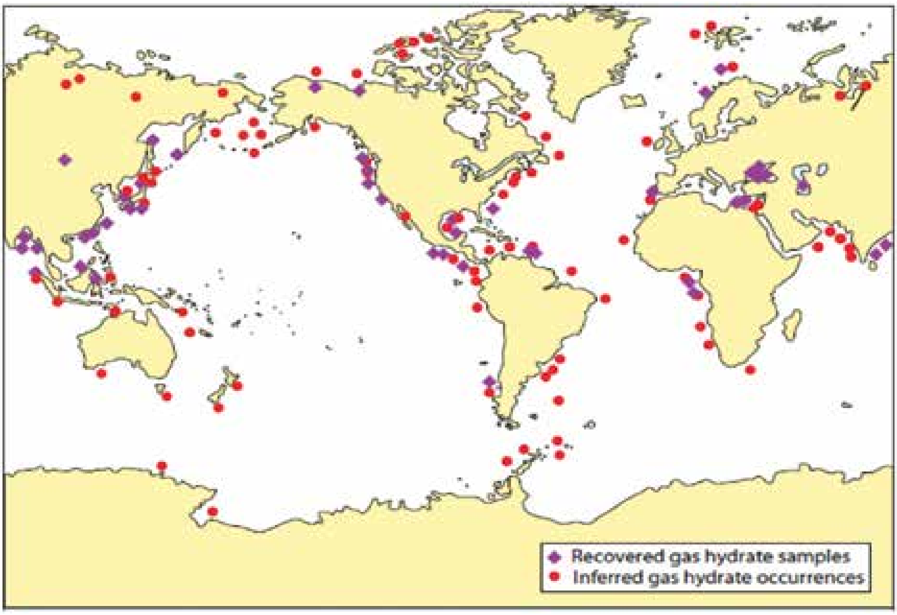


Figure 8. Transforming CO_2 from a liability to an asset.

In conclusion: can we foresee a new age of fossil-generated abundance? Our new method of Hydrogen production associated with the very large resources of newly discovered NG – eventually converted into Methanol, whenever a fuel is required in the liquid form – would permit to continue the safe supply of an already widely available fossil fuel at low cost, eliminating the ordinary environmental drawbacks of an ordinary NG combustion.

In view of the well-known, serious environmental concerns, the technology of methane de-carburation and no CO_2 emissions could become one of the primary energy sources during the decades to come.

The energy innovation process is generally characterised by long lead times, often decades, to achieve substantial markets, due to the scale of investments needed and the technological and regulatory inertia inherent in existing energy systems.

Public intervention to support energy innovation is thus both necessary and justified.

References

[1] Herzog, H., Eliassou, B., Kaarstad, O.: Capturing Greenhouse Gases, *Scientific American* vol. 282, No. 2, pp. 72-79, February 2000.

[2] Robock, Alan, Allison B. Marquardt, Ben Kravitz, and Georgiy Stenchikov, 2009: The benefits, risks, and costs of stratospheric geo-engineering. *Geophys. Res. Lett.*, 36, L19703, doi:10.1029/ 2009GL039209.

[3] M. C-F. Volney, Travels through Syria and Egypt, in the years 1783, 1784, and 1785, Vol. I, Dublin, 258 pp. (1788).

Solar Cells and Solar Energy

Klaus von Klitzing

In this discussion, I will focus on the topic of solar cells and solar energy. I have worked my entire life in the field of semiconductor physics, which is the basis of solar energy technology.

It has been predicted that there will be no life on Earth in 5 billion years. By that time, sunlight will irradiate the Earth directly and unfiltered, which will eliminate life as we know it. In other words, life on Earth is not sustainable on the time scale of billions of years. The question we face, however, is whether life will be sustainable in the next ten, one hundred or one thousand years. Moreover, we should focus on man-made environmental issues, not on natural phenomena. It has also been predicted that, in 5 billion years, thousands of new worlds will exist, so this gives us some time to deal with our environmental challenges, to communicate with beings on other planets, and to transfer our knowledge to other civilizations.

New Global System of Measurement Units

There is something much more stable than life on earth, and that is the universal language of science. In the past, documented as far back as in the Bible, we used local units based on human dimensions to measure length and mass, such as ell, cubit, foot or grain. However, these measures differed throughout the world.

For the past 150 years, we have used standardized global units based on properties of the Earth to measure time, length, mass etc. For example, we use the rotation of the Earth as a basic time unit and the dimensions of our planet for units of length. However, in just two years' time, we will use a new global system of units that is independent of both humans and the Earth. Starting in 2019, we will have stable, universal units based on fixed values for constants of nature. Because just imagine, if the prototype of the kilogram in Paris were no longer to exist in some billions of years, we would still have a universally defined kilogram based on the fundamental Planck constant.

Energy: The Driving Force behind (Borrowed) Prosperity

For the purpose of this discussion, let us consider a pragmatic definition of sustainability: To ensure a desirable planet for the next three generations.

This is a near-term goal. First, to answer the question of what constitutes a "desirable" planet, we must recognize the crucial role played by sustainable energy. To wit, former UN Secretary General Ban Ki-moon has defined sustainable energy as "The golden thread that connects economic growth, increased social equity and an environment that allows the world to thrive." (Ki-moon, 2014). Energy, preferably electrical energy, is not only the driving force of economic wealth but also a necessity for a decent standard of living in a world with an increasing population. We have been lucky enough so far to have lived in this world of ever increasing energy consumption with growing affluence. But as we now realize, this has been at the expense of future generations. Two-thirds of the world's electrical energy used today is generated by burning fossil fuels (https://en.wikipedia.org/wiki/Electricity_generation). We must now also face the consequence that it will take us only a few more hundred years to destroy the reservoir of coal, oil and natural gas that took more than 70 million years to form. Therefore, the context of time must be an integral part of our sustainability discussions.

Atmospheric CO_2

It has been well established that the CO_2 content in our atmosphere has increased from less than 320 ppm in 1960 to more than 400 ppm today, accompanied by a rise in global temperature. We need to curb these CO_2 emissions. Although some progress has been made in this respect, if we extrapolate the current trend to the next few decades, there is no chance that atmospheric CO_2 can be kept below the limit of 450 ppm, which is considered necessary in order to avoid global warming of more than 2 degrees Celsius by 2100 (https://www.esrl.noaa.gov/gmd/obop/mlo/). This means that radical changes must be made within the next five years.

The problem for some non-scientists, however, is that we cannot actually see CO_2, so it is easy to deny its impact on our environment. However, there are special cameras that can capture images of CO_2 emissions. We are emitting CO_2 into our atmosphere at an alarming rate. Many scientists – even many physicists – do not realize that burning just one liter of gasoline creates 2.33 kilograms of CO_2. These are huge amounts we are emitting constantly into our air, and we need to do more to educate the public about these emissions and their impact on the environment.

Resources for Energy Production

Several natural energy reservoirs exist on our planet, but they have become depleted over time. These natural energy reservoirs include coal, natural gas, petroleum and uranium. In contrast, the amount of solar energy is truly huge. The sun emits more than enough energy to Earth in just one hour to meet our global energy demands for an entire year (http://www.asrc.albany.edu/people/faculty/perez/). All the other natural energy reservoirs are but secondary results of solar energy. It is of course well known that we have the technology to transform solar energy directly into electricity. However, the percentage of photovoltaic energy produced is still very small at less than 0.1% of the world's consumption at the beginning of this century. The excuses are as numerous as they are misguided: photovoltaic energy is too expensive, has no future, etc. Indeed, predictions for the use of photovoltaic energy have been pessimistic, but fortunately, this is changing. Nevertheless, the amount of solar energy being harnessed is still a very low percentage of the available resource. Fortunately, the cumulative photovoltaic capacity has increased exponentially and has always been much greater than predicted by the IEA's (International Energy Agency) World Energy Outlook (Schmalensee *et al.*, 2015). Clearly, we need to increase our production of solar energy greatly in order to take full advantage of this huge resource.

Let us also examine the economic factors involved. The cost per module of photovoltaic cells per Watt has fallen drastically from about \$100 in 1976 to just \$0.45 in 2016 (https://commons.wikimedia.org/wiki/File:Swansons-law.png). In 2008, more silicon wafers were used for solar cells than for microelectronic devices (Gunawan *et al.*, 2010). In other words, the huge global market for solar cells emerged in this century. More importantly, the costs of photovoltaic cells will soon become competitive with those of coal or natural gas, making them even more interesting from an economic perspective (Shenkleman & Martin, 2017). Therefore, it is only logical that, as the cost of photovoltaic panels has decreased, the global number of solar panel installations has risen accordingly.

Silicon: The Backbone of Photovoltaic Mass Production

Although various materials are of interest in semiconductor physics, silicon is still the backbone not only of microelectronics but also of photovoltaics. In fact, 90% of the global photovoltaic technology market is covered by crystalline silicon for today's most efficient photovoltaic cells (20% efficiency). However, there are many other, possibly even more successful semiconductor materials such as cadmium telluride (CdTe), copper-indium-gallium-selenide (CuInGaSe) as well as perovskites. In fact, CdTe appears to be better attuned to the solar spectrum, making it a potentially important future candidate for photovoltaic technology. Ultimately, the market price will determine which materials will be successful. Special applications, such as for the aerospace industry, use very expensive semiconductors with a long lifetime known as III-V materials that encompass the entire solar spectrum. For example, three semiconducting materials that together cover the main part of the solar spectrum are gallium-indium-phosphide (GaInP), gallium-indium-arsenic (GaInAs) and germanium (Ge). Scientists are currently developing such high-efficiency, triple-junction solar cells based on III-V materials for the mass market. This technology allows us to concentrate the sun's radiation for record efficiencies of up to 46% (https://en.wikipedia.org/wiki/Solar_cell_efficiency). However, the effort to cover 15% of the global electricity production with solar energy is still in its infancy. To achieve that, we must increase investments into solar energy technology. Fortunately, the rapid introduction of photovoltaics globally is being fueled by the availability of cost-competitive, distributed energy producers. Some analysts predict that photovoltaic installations worldwide will generate 4,000 to 30,000 GW by the year 2050. For comparison, today's photovoltaic installations worldwide generate less than 300 GW.

Renewable electricity sources are not yet able to meet the growing global power consumption. Even if we increase the current amount of photovoltaic energy, we will not keep pace with future demands.

Conclusion

In conclusion, primary and secondary renewable energy sources such as solar, wind and biomass will play a central role in the future energy transition. Ultimately, the greatest promise lies in combining large-scale solar power plants and small-scale, building-integrated solar energy generators (Perez, 2010). Clean energy technologies are already cheaper than traditional sources such as coal, and the economy is always a major driving force. Therefore, we can safely predict that clean energy has a bright future.

References

Gunawan, O., Wang, K., Fallahazad, B., Zhang, Y., Tutuc, E., & Guha, S. (2011). High performance wire-array silicon solar cells. In *Prog. Photovolt: Res. Appl.*, (pp. 307-312). J. Wiley & Sons. doi:10.1002/pip.1027.

Ki-moon, B. (2014). Sustainable Energy 'Golden Thread' Connecting Economic Growth, Increased Social Equity, Secretary-General Tells Ministerial Meeting. Retrieved from https://www.un.org/press/en/2014/sgsm15839.doc.htm

Perez, R. (2009, Autumn) Renewable Energies. Our Solar Future. Daylight & Architecture, pp. 2-8. Retrieved from http://www.asrc.cestm.albany.edu/perez/2010/DA12_perez.pdf

Schmalensee, R., Bulovic, V., Armstrong, R., Batlle, C., Brown, P., Deutch, J., Jacoby, H., Jaffe, R., Jean, J., Miller, R., O'Sullivan, F., Parsons, J., Pérez-Arriaga, J.I., Seifkar, N., Stoner R., & Vergara. C. (2015). The Future of Solar Energy: An Interdisciplinary MIT Study. Massachusetts Institute of Technology, MIT Energy Initiative. Retrieved from http://mitei.mit.edu/futureofsolar

Shankleman, J., & Martin, C. (2017, January 3). Solar Could Beat Coal to Become the Cheapest Power on Earth. Retrieved from https://www.bloomberg.com/news/articles/2017-01-03/for-cheapest-power-on-earth-look-skyward-as-coal-falls-to-

Sustainable Thorium Energy for the World

Jean-Pierre Charles Revol[1]

1. Sustainability

Nothing is sustainable in the long run, not our sun and, of course, not life on this planet. In about 550 million years, it is expected that photosynthesis will cease through lack of carbon dioxide [1], which is somewhat ironic, given today's worries concerning global warming. Hence, life as we know it will no longer be possible on Earth, and we can only speculate on the fate of humankind, as it is not predictable on such a long timescale. Sustainability only makes sense as a relative concept with respect to the human timescale. The definition of sustainability may become complex when adding environmental, economic, or social considerations. For our purpose, a sustainable energy source could be defined as a source of energy with reasonably manageable impact on the environment, and one that will last

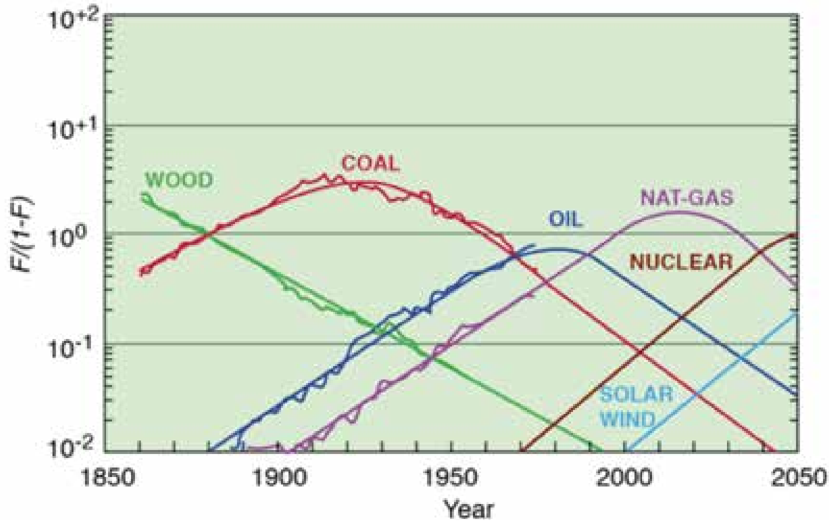


Figure 1. The substitution model applied to the dynamics of energy systems by C. Marchetti and N. Nakicenovic (1979) [2], for the period 1860–2050, where F is the fractional market share.

[1] International Thorium Energy Committee, Geneva, Switzerland and Centro Fermi, Rome, Italy

long enough for an innovative technology to provide a replacement. A scenario of clear successive energy substitutions has been observed in the past, as shown by Cesare Marchetti [2] (Fig. 1), with energy market niches for wood being successively substituted by coal, oil, and natural gas. The picture has dramatically changed today (Fig. 2), as nuclear energy did not live up to expectations, while newly discovered reserves of coal, gas, and oil have extended the dominance of fossil fuels, and renewable energies have experienced difficulties in conquering a substantial part of the world market.

Sustainability clearly demands an adequate R&D effort for the next innovation to become available in time. In addition, the research effort must include fundamental research, as it is fundamental research that drives innovation. Most importantly, the R&D effort must be accompanied by substantial investment in education in order to provide the required number of researchers, but also to raise the awareness of the public. Without a sufficient effort in education and R&D there is a danger that humankind will exhaust the natural energy resources of the planet before new innovative energy sources are made available.

With our definition, solar energy clearly is a sustainable source of energy, although present solar energy photovoltaic technologies may not (yet) be sustainable owing to constraints on the availability of rare materials such as indium, tellurium, germanium, and ruthenium if one wants to scale up

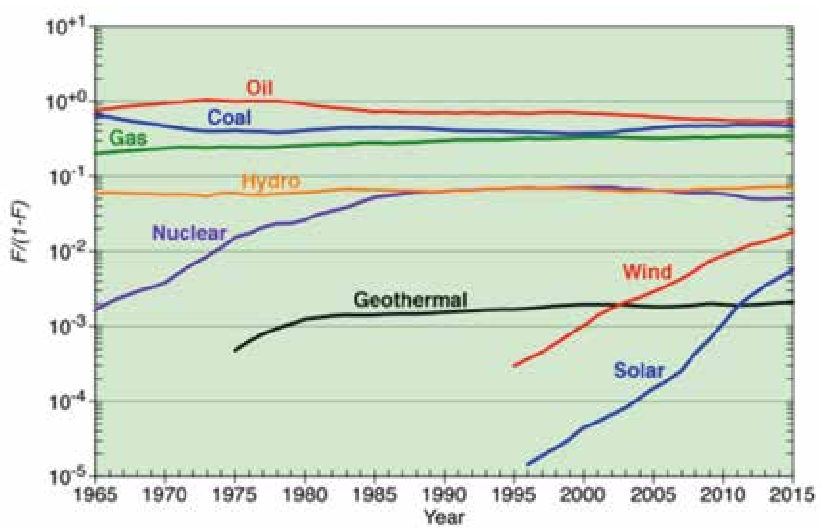


Figure 2. C. Marchetti's quantity F/(1–F), where F is the fractional primary energy consumption as a function of time, using data for the period 1965-2015 from [3].

the solar energy technology to the TW level [4]. Clearly, nuclear energy as we exploit it today is not sustainable. On the other hand, a new source of energy that would last 20 centuries or more and that would meet the basic requirements in terms of environmental impact, would clearly qualify as sustainable. This is potentially the case for thorium energy as will be discussed in sections 4 to 8.

2. Replacing fossil fuels: a major challenge for society

Fossil fuels, which have been dominating the energy market for over 150 years, are present in finite quantities in the Earth's crust and inevitably will run out sooner or later. At the rate they are being used today, the timescale for exhausting these sources of energy is of the order of 50 to 100 years for oil and gas, and 100 to 150 years for coal. If consumption continues to increase, the end of fossil fuels will occur sooner. This should be of significant concern not only because of the short time periods with their attendant implications, but also because it certainly does not make sense to continue burning fossil fuels until supplies run out for several strong reasons:

– In the first place, there is an increasing consensus that global warming as a result of the release of greenhouse gases issuing from human activities is a serious problem. Even if this is still doubted by some, precaution should prevail. We should stop releasing massive amounts of CO2 and other greenhouse gases into the Earth's atmosphere. The year 2016 saw the CO_2 concentration exceed 400 ppm [5], a level and a rate of increase unprecedented in at least the past million years.

– Air pollution produced by burning fossil fuels is an immediate, real, and very costly major problem. Burning coal costs Europe alone over 40 billion Euros in annual healthcare expenses [6]. In 2015, the European Environmental Agency declared that: "Air pollution poses the single largest environmental health risk in Europe today". Close to one million deaths per year in China are due to air pollution [7]. The World Health Organization (WHO) estimates that one in eight total deaths in the world are the result of exposure to air pollution [8]. This means that fossil fuels kill twenty thousand people each day. Why is this not the prime reason put forward for wanting to stop burning fossil fuels?

– Remaining fossil fuel reserves could certainly be put to much better use, instead of burning them. For instance, oil is used in the manufacture of plastics, rubber, paints, glue, drugs, cosmetics, detergents, asphalt for roads, etc., and perhaps most importantly, chemical fertilizers, which are crucial to our food supply.

Despite all this, in 2015, fossil fuels still represented 86% of the primary energy consumption [3] (Fig. 3), and because they are cheap and abundant, the current tendency is to increase their consumption (Fig. 4). Assuming a globally rising standard of living and a global population plateauing between 10 and 11 billion inhabitants, it is expected that the world energy consumption would have to increase by a factor of three or more in the next 100 years to keep pace with expected demand. Our civilization would then be powered as a 45 TW engine exceeding the 44 TW geothermal power of the planet.

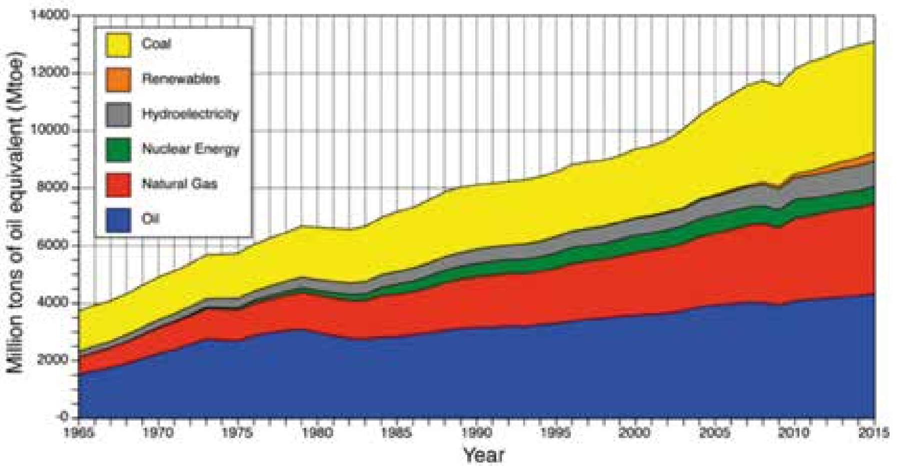


Figure 3. World primary energy consumption [3] for the period 1965-2015. Coal, gas, and oil represent 86% of the supply, hydro 6.8%, nuclear 4.4%, and renewables 2.8%.

Our vision of global energy issues is obscured by the fact that Europe is not representative of the rest of the world: it is one of the rare regions of the world where the population is expected to decrease [9], there is essentially no economic growth, and European citizens enjoy one of the highest standards of living. Clearly, one cannot imagine applying to the 1.2 billion people in the world still without electricity the same energy measures presently proposed by European politicians.

Figure 4. Primary energy consumption of fossil fuels (coal, gas, and oil combined) in million tons of oil equivalent (Mtoe) for the period 1965–2015. Data were extracted from [3].

3. Nuclear fission energy can be exploited in a different way

Solutions to the energy problem can only come from intensive and systematic R&D. Developed countries, which have enjoyed cheap but polluting energy supplies without limit in order to achieve their present level of wealth, have the responsibility to lead the R&D effort and develop innovative solutions. It is clearly a responsibility for the scientist to feed the R&D effort. Politicians cannot invent solutions. Funding does not even seem to be a limitation in Europe, if we may judge from the 600 billion Euros that the EU spent on renewable energies from 2005 to 2013 [10], mostly on subsidies.

Nuclear fission energy must not be left out of the energy R&D effort. Resources are abundant and energy-intensive. For instance, an electric power of 1 GW can be sustained for one year by using only 1 ton of thorium, compared with 3 to 4 million tons of coal or 60 km2 of solar cells at the latitude of Paris. Nuclear fission energy can ensure base load electricity production, it produces neither greenhouse gases nor air pollution, and it could be made sustainable. If it were not for accidents, waste management, and proliferation issues, there would be no reason to want to stop nuclear power plants. So the question that should be asked is: *Can nuclear energy be made acceptable to society?* It is clear that the present way of exploiting nuclear energy was selected for other reasons: the uranium fuel cycle was chosen to produce plutonium for nuclear bombs; Pressurized Water Reactors (PWRs) were invented to fit on a submarine. Is there a better choice for nuclear energy? Prominent physicists, such as Nobel Prize Laureate Carlo Rubbia, answered clearly "yes", with thorium fuel in fast neutron Accelerator-Driven Systems (ADS) [11]. This is not to claim that thorium accelerator-driven systems could by themselves solve the entire energy problem, but they would make a major contribution to the solution, by allowing nuclear energy to take a major share of the energy mix and by being complementary[2] to renewable energies, while at the same time offering the possibility of destroying a major fraction of nuclear waste. Regardless of national policies, the problem of nuclear waste management must be solved, as waste has accumulated and continues to accumulate (Fig. 5). The added requirement of retrievability makes geological storage more challenging if not questionable; therefore, alternative solutions must be considered.

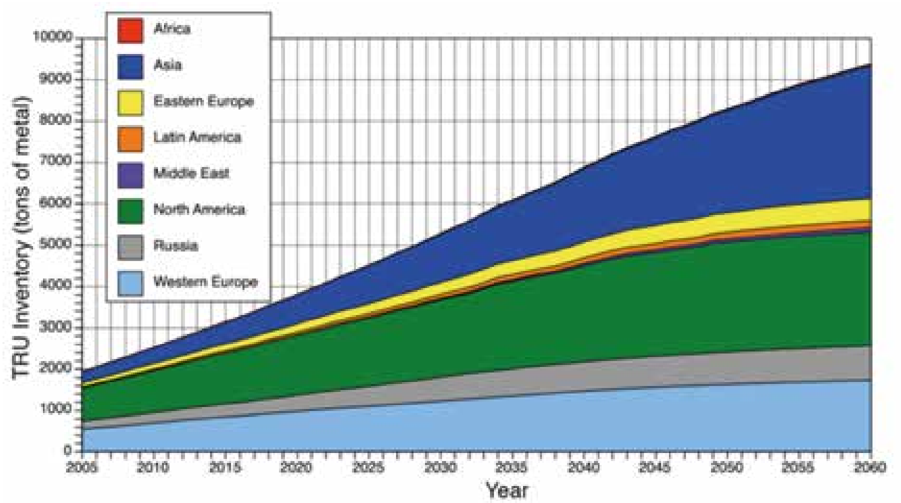


Figure 5. Evolution of the world inventory of transuranium elements (TRU)[3], the long-lived component of nuclear waste, in tons, and projection to 2060, assuming the present number of nuclear reactors and those expected to be commissioned by 2035, showing that TRU waste will exceed 9000 tons by 2060 [12].

[2] Photovoltaic solar energy and wind energy require another source of energy with equivalent power as a backup for when there is no wind or no sun, because of the lack of technology suitable for massive electricity storage. The plan in Germany is to use coal-fired power plants for this purpose.

[3] TRU: chemical elements with atomic numbers greater than 92 (the atomic number of uranium).

4. Thorium: a sustainable source of energy

Given the foreseeable huge energy demand, any potentially important source of energy must be considered, in particular thorium, as the technologies required to exploit it represent only a relatively modest extrapolation of existing nuclear reactor and particle accelerator technologies, in sharp contrast to the development of fusion energy.

Table 1. Estimated world thorium resources in tons [13]. Note that one ton of thorium can generate 1 GW of electric power for one year.

	Country	Quantity (ton)		Country	Quantity (ton)
1	India	846,000	10	South Africa	148,000
2	Brazil	632,000	11	China	100,000
3	Australia	595,000	12	Norway	87,000
4	USA	595,000	13	Greenland	86,000
5	Egypt	380,000	14	Finland	60,000
6	Turkey	374,000	15	Sweden	50,000
7	Venezuela	300,000	16	Kazakhstan	50,000
8	Canada	172,000		Other countries	1,725,000
9	Russia	155,000		**World Total**	**6,355,000**

It is estimated that the Earth's crust contains 1.2×1014 tons of thorium [14], which is about the same amount as lead, and three to four times more than uranium. Thorium resources are broadly distributed on the Earth (Table 1), which has obvious geopolitical advantages. Thorium is not fissionable, so one must produce the uranium-233 isotope from thorium to obtain fissions (Fig. 6). Breeding of uranium-233 uses essentially all the thorium. In PWRs, it is only uranium-235, present at a level of 0.7% in natural uranium, which is used. As a result, thorium represents a greater energy supply by a factor of 140, which, when combined with the higher thorium abundance, corresponds to an overall factor of 500 times more potential thorium resources compared with uranium.

Assuming the present world electric power consumption of 2.5 TW, the 6.3 million tons of thorium reserves [13] (Table 1), a number probably underestimated given that thorium has not been the object of a systematic search, could electrically power the whole planet for 2500 years. At the ThEC13 international conference on thorium at CERN, Carlo Rubbia

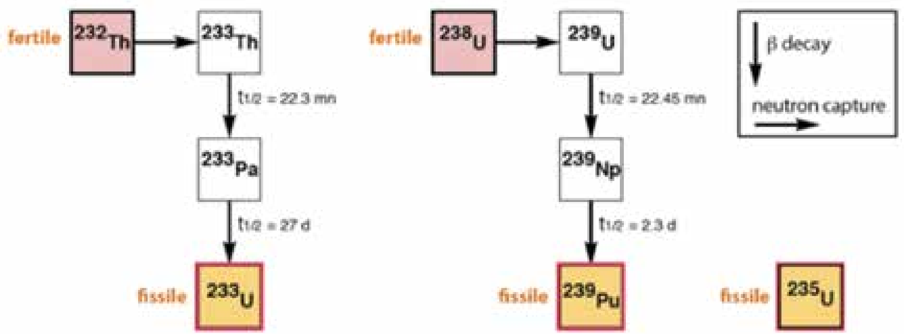


Figure 6. The three main nuclear fuels are U-233, Pu-239, and U-235. The figure shows a comparison of the breeding schemes for U-233 in thorium fuel (left) and for Pu-239 in uranium fuel (middle). U-235 used in present PWRs does not require breeding as it is extracted from natural uranium, where it is present at the 0.7% level. Horizontal arrows represent neutron captures, and vertical arrows β decays.

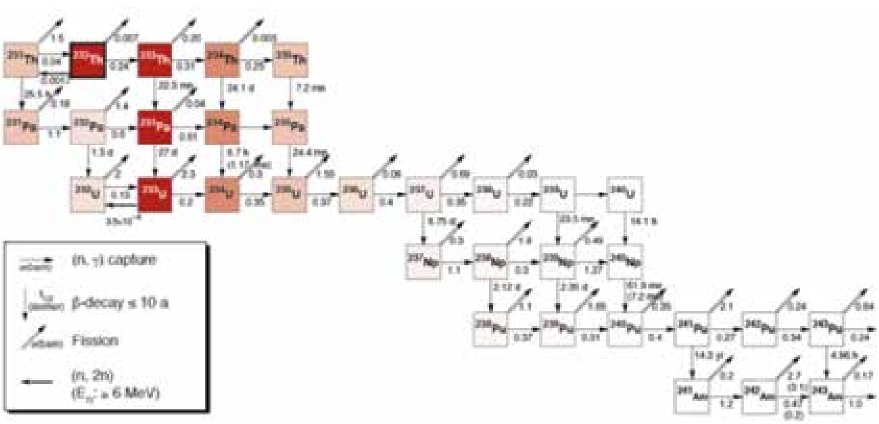


Figure 7. Main elements produced by irradiation of thorium in a fast neutron flux, illustrating why the production of TRU is strongly suppressed, as it takes six successive neutron captures to produce uranium-238 starting from thorium-232. Horizontal arrows represent neutron captures, vertical arrows b decays, and diagonal arrows fissions.

stated: "Thorium constitutes a sustainable energy resource on the human timescale" [15].

Natural thorium is isotopically pure, found mostly in monazite ores, but also in thorite ($ThSiO_4$) and in thorianite (ThO_2+UO_2), and is relatively cheap as it is often a by-product of rare earth mining. Thorium produces smaller amounts of long-lived nuclear waste (TRU) than uranium, because it is six neutron captures away from uranium-238, the entry point for the production of TRU in the neutron irradiation chain (Fig. 7). In addition, thorium has excellent physical properties such as higher melting points for both the metallic and oxide forms, and better thermal conductivity compared with uranium. This means that there are higher safety margins for design and operation. Most importantly, the thorium fuel cycle has the great advantage of being proliferation resistant, as the production of plutonium is negligible and the uranium mixture in the spent fuel makes it extremely difficult to manufacture a bomb [11].

Because of the need for breeding uranium-233 to obtain fissions, and for neutron inventory reasons, thorium cannot simply be substituted for uranium in critical reactor fuel. Three basic approaches are envisaged today in order to exploit thorium [16]:

a) A three-stage scheme adopted by India [17]. This involves breeding plutonium in CANDU heavy water reactors, then using the plutonium produced as the fuel in fast sodium-cooled critical reactors, around which uranium-233 is bred in a thorium blanket. Finally, the uranium-233 extracted from the blanket is used to manufacture fuel for advanced thermal reactors. This scheme is complicated, as it requires maintaining three different reactor technologies. Moreover, it does not solve the problem of nuclear waste management and it is not sustainable as uranium is needed to initiate the process.

b) Moving the fuel continuously in order to always have fresh fuel in the core. This can be done in pebble-bed reactors [18] or in molten salt reactors [19], both of which have serious technical and safety issues still to be resolved. There exists also the idea, yet to be developed, of traveling wave reactors [20]. In these systems, it is not the fuel that moves, but the neutron breeding and fission wave.

c) Using a particle accelerator to produce the extra neutrons needed to sustain a chain reaction, in so-called subcritical accelerator-driven systems (Fig. 8). This appears to be the most efficient and elegant method for using thorium [11] and, when used in fast neutron ADS, a most efficient method for destroying TRU through fission.

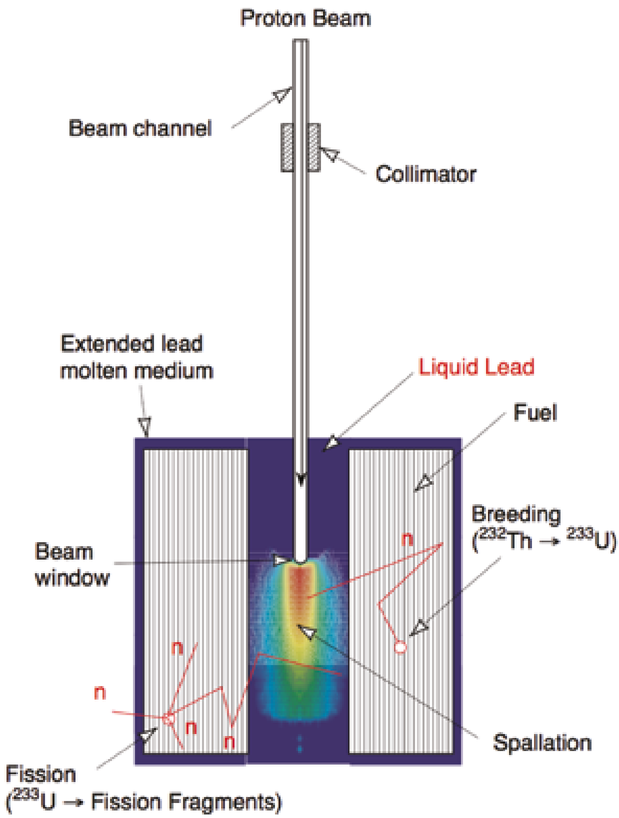


Figure 8. Principle of an accelerator-driven system. A proton beam inserted vertically from the top hits a lead target, producing neutrons through the spallation process. These neutrons travel to the subcritical core, where they are amplified by fission processes similar to those at work in a critical nuclear reactor. The system is called "subcritical" because the chain reaction is not self-sustained; it is powered by the proton beam, which can be switched off in a few microseconds.

5. Fast neutron ADS: a technology feasible today

The ADS idea could perhaps be traced back to the first particle accelerator, in which the radioactive element polonium-210 was used, in 1919, by Ernest Rutherford to bombard nitrogen-14 with 5.3 MeV α particles to produce oxygen-17. An important milestone was certainly 1940, when Ernest O. Lawrence in the USA and Nikolay N. Semyonov in the USSR independently proposed using a particle accelerator as a neutron source. This could be considered as the birth of ADS, and shortly after that, in

1942, Glenn Seaborg produced the first μg of plutonium-239 by using a cyclotron.

Early ADS projects in the 1950s were abandoned when it was realized that the accelerator technology was not yet ready for the required beam power. Renewed interest in ADS in the 1980s appeared under the impetus of Hiroshi Takahashi [21] at Brookhaven National Laboratory and of Charles D. Bowman [22] at Los Alamos, when the USA decided to slow down the development of fast critical reactors.

In the 1990s, Carlo Rubbia gave ADS a major push [11] by launching a vigorous research program at CERN based on the development of innovative simulations of nuclear systems, by using particle physics Monte Carlo simulation methods, and by carrying out specific experiments to test basic concepts (FEAT [23] and TARC [24] experiments). Rubbia is at the origin of the concept, design, and construction of the advanced neutron Time of Flight facility (n_TOF) [25], now in operation at CERN, to acquire neutron cross-section data, crucial for simulating any configuration with new materials.

The conclusion of the CERN study is that thorium must be used in a fast neutron flux ADS to favor breeding (Fig. 9), to allow long burnups for better fuel usage efficiency and longer operation time (neutron captures on fission fragments are much smaller than in a thermal neutron flux), and

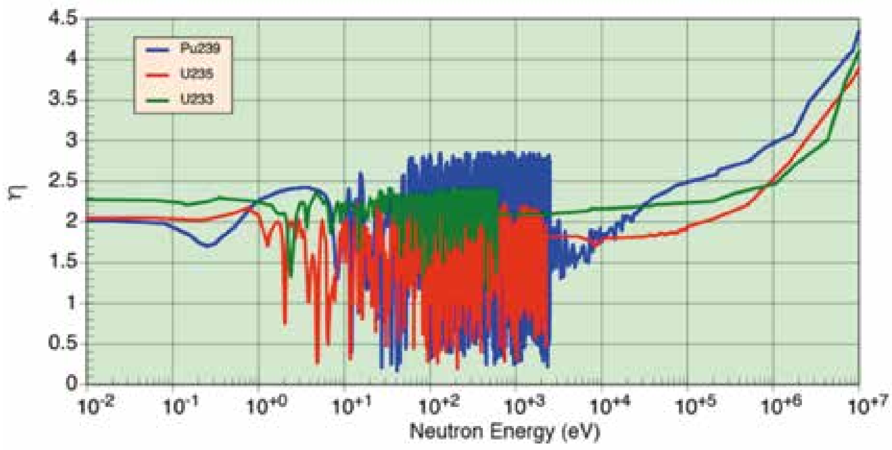


Figure 9. Number of neutrons produced per neutron absorbed (η) in U-233, U-235, and Pu-239, as a function of neutron kinetic energy, taken from [26]. For breeding to be possible, η has to be larger than 2. The fast neutron part of the spectrum is clearly advantageous for breeding, even though, for U-233, breeding is also possible at thermal and epithermal neutron energies.

finally because TRU can fission in a fast neutron flux, and therefore be eliminated by recycling them as fuel. The 9400 tons of TRU expected to accumulate by 2060 (Fig. 5) could power the entire world electrically at the present level of 2.5 TW for 3.7 years.

The first phase of ADS development, which consisted of validating the basic concepts, was completed in the 1990s, in particular at CERN. In the second phase, which was completed in the 2000s, all the basic elements of an ADS were tested separately. Proton beams have exceeded a power of 1 MW, first achieved at the Paul Scherrer Institute (PSI) in Switzerland, with a cyclotron [27]. During the same time period, neutron spallation sources have reached or exceeded the MW regime, first with MEGAPIE [28] at PSI and nowadays with the Spallation Neutron Source (SNS) [29], at Oak Ridge National Laboratory, in the USA, which runs at 1.4 MW beam power. Today, the European spallation neutron source (ESS) [30], with 5 MW beam power is under construction in Sweden and EURISOL [31] is being designed for a beam power of 4 to 5 MW, and is awaiting funding for construction. The proton accelerator community has made decisive progress in the development of high-power superconducting accelerating cavities. EUROTRANS, a major R&D program of the European Union 5th and 6th framework programmes on partitioning and transmutation for

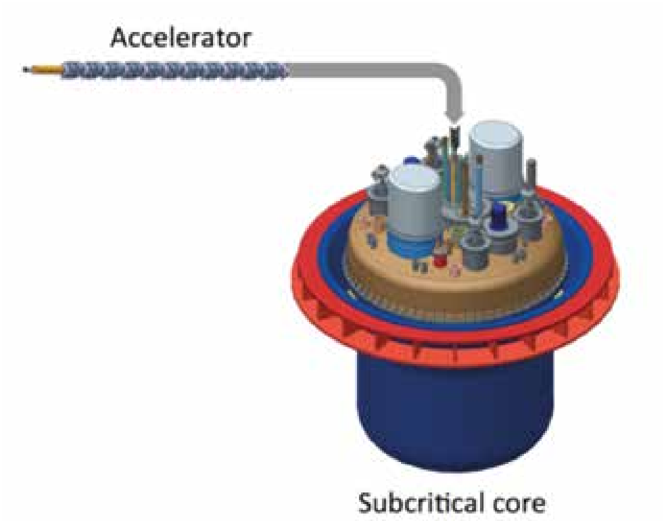


Figure 10. Schematics of the MYRRHA ADS, with a proton linear accelerator (600 MeV, 2.5 mA) driving a subcritical core, cooled with a eutectic lead–bismuth mixture, designed to produce a thermal power of 50 to 100 MW.

the uranium fuel cycle, has addressed all the aspects of the back end of the nuclear fuel cycle, as well as corrosion issues with high-temperature lead or lead-bismuth coolants.

As all the elements of an industrial ADS exist separately, the next step, or phase 3, should logically consist of a first coupling at significant power (≥1 MW) of a proton beam to a fast neutron subcritical core. However, this step is still missing, more than 20 years after the pioneering FEAT experiment. Phase 3 should include the development of an accelerator optimized for industrial applications of ADS.

The good news is that there are two major ADS projects in the world today, driven by proton linacs (linear accelerators), which are aimed directly at what could be defined as the industrial fourth phase: the MYRRHA project [32] in Europe (Fig. 10), which should be the flagship of accelerator-driven systems, and ADANES [33] in China, which has the goal of reaching 1000 MW of electrical power by 2032. Given their long timescales (for both projects, first operation is not expected before the 2030s) and the large leap into industrialization, both projects would benefit from an ADS phase 3. In India, there is also interest in ADS, and the HISPA project [34] at the Bhabha Atomic Research Center is concentrating on the development of a high-power proton linac, with a first stage goal of a 30 mA, 20 MeV injector, and the ambition to reach 1 GeV and 30 MW beam power for the final stage.

There are also several other on-going ADS-related activities in the world, for instance, in Ukraine, with a 100 kW, 100 MeV electron beam driving a subcritical thermal core [35], just about to be commissioned, and in Japan [36], where ADS research was restarted as a consequence of the Fukushima accident. Given the importance of the energy issue, the lack of coordination and collaboration between these various efforts is regrettable.

6. iThEC's initiatives: a first accelerator–subcritical core coupling experiment

iThEC, the international Thorium Energy Committee [37], is a Geneva-based, non-profit association, founded under Swiss law in 2012, with the goal of promoting R&D in the use of thorium to transmute nuclear waste and produce safe, clean, and abundant energy, in particular with accelerator-driven systems.

iThEC became convinced of a rather unique opportunity in Russia, at the Troitsk INR laboratory, where the existing infrastructure (Fig. 11) would allow, for the first time at significant power (a few MW), the coupling of

Figure 11. Photograph of the INR Troitsk beam target area showing the proposed ADS pit (1), the presently operating pulsed neutron source cell (2), and its beam line (3). Taken from [38].

a proton accelerator to a fast neutron subcritical core. The accelerator exists and needs only a relatively modest refurbishment to operate at a beam power of 30 to 90 kW, with 300 MeV protons. Troitsk is already operating a neutron spallation source. A beam line toward an available experimental pit could be implemented quickly. In addition, the infrastructure exists for the manipulation of radioactive materials. In five years' time a landmark experiment could be carried out, which would measure the properties of a MW fast neutron thorium ADS, demonstrate its safety, demonstrate the destruction of minor actinides, and test new possibilities for the production of radioisotopes for medicine. This would be at a cost of less than 4% of currents projects such as MYRRHA, and would provide invaluable information for the current large projects in Europe and China. The political impact of a first demonstration of destruction of nuclear waste would probably be very important. A road map of the project has been prepared jointly by INR management and iThEC. The Troitsk experiment would constitute, in addition, a versatile fast neutron test facility, the subcritical character of which guarantees safety. If approved by Russian authorities, the project is expected to get international support and a collaboration on the CERN experimental collaboration model would be possible. However, at this time, iThEC is still looking for a funding scheme to initiate the project.

7. iThEC's initiatives: an innovative high-power superconducting cyclotron

The second iThEC initiative is a project to be submitted to the European Union under the framework of the Horizon 2020 FET program [39]. It is a collaboration with CERN, PSI, ENEA [40] in Italy, and leading European industrial companies to design an innovative single-stage, high-power superconducting cyclotron [41] (Fig. 12). Reliability, minimal beam losses, and a much lower cost than other technologies are the main goals of the study. The ultimate goal of the project is to demonstrate that, for industrial applications, the cyclotron option is favorable.

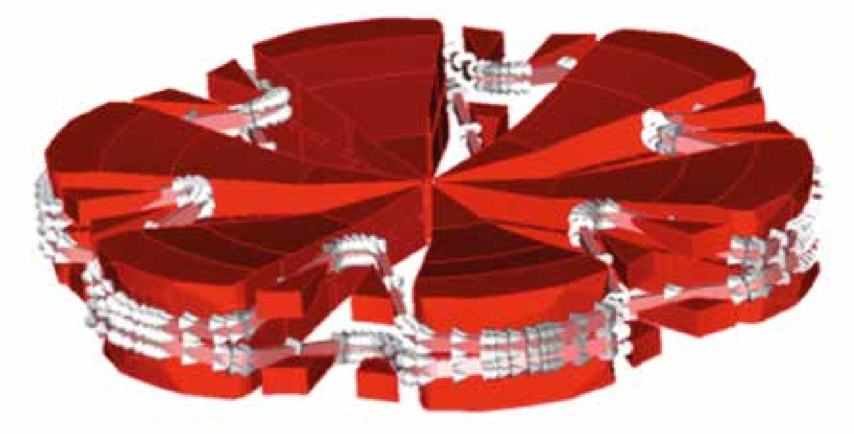


Figure 12. 3D view of the six-sector, single-stage cyclotron with reversed valley B-field (patented under the name S2CD by AIMA DEVELOPPEMENT), considered for the Horizon 2020 FET proposal [41].

8. Conclusion

Sustainability requires innovation. Sustainability of the world energy supply can only be achieved through a vigorous and systematic R&D effort, including R&D in the domain of nuclear fission energy, in order to develop acceptable methods for its safe exploitation. Fossil fuels are not a sustainable source of energy and they have a disastrous impact on the environment, however, replacing them to achieve a zero-carbon society is probably one of the greatest challenges faced by society today.

Whether a country decides to stop or continue its nuclear program, or in the case of developing countries, to start a nuclear program, the issue of nuclear waste management remains to be resolved.

ADS with thorium fuel offer the possibility to destroy a major part of the long-lived waste inventory to reduce the need for long-term storage, while at the same time producing energy. For energy production, there would be synergy between renewables and thorium ADS, as the power from ADS can be modulated to follow the fluctuations of wind and solar energies.

Thorium is an abundant and sustainable source of energy for the future, one that society cannot afford to ignore.

References

[1] Lovelock, J.E., Whitfield, M., Nature *296*, 561-563 (1982); Caldeira, K., Kasting, J.F., *Nature 360*, 721-723 (1992); Lenton, T.M., von Bloh, W., *Geophys. Res. Lett. 28*, 1715-1718 (2001); Li, K., Pahlevan, K., Kirschvink, J.L., Yung, Y.L., Proc. Nat. Acad. Sci. *106*, 9576-9579 (2009).

[2] Marchetti, C., *Stable Rules in Social and Economic Behavior*, International Institute for Applied Systems Analysis, A-2361, Laxenburg, Austria, 1986; Marchetti, C., Nakicenovic, N., *The Dynamics of Energy Systems and the Logistic Substitution Model*, CIIASA Research Report (December 1979).

[3] BP Statistical Review of World Energy, 65th edition (June 8, 2016).

[4] Grandell, L., Höök, M., *Assessing Rare Metal Availability Challenges for Solar Energy Technologies*, Sustainability 7, 11818-11837 (2015); DOI: 10.3390/su70911818.

[5] WMO Greenhouse Gas Bulletin, *The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2015*, No. 12 (October 24, 2016).

[6] Health and Environment Alliance Report, *The Unpaid Health Bill* (2013).

[7] GBD MAPS Working Group, *Burden of Disease Attributable to Coal-Burning and Other Air Pollution Sources in China*, Tsinghua University Report (2016).

[8] WHO Report (March 25, 2014).

[9] World Population Prospects, the 2015 Revision, United Nations, Department of Economic and Social Affairs, Population Division.

[10] Liebreich, M., Bloomberg New Energy Finance, BNEF Summit Keynote (April 23, 2013).

[11] Rubbia, C., et al., *Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier*, CERN/AT/95-44 (ET) (September 29, 1995); see also: Rubbia, C., *A High Gain Energy Amplifier Operated with Fast Neutrons*, AIP Conference Proc. 346, Int. Conf. on ADT Technologies and Applications, Las Vegas, Nevada, USA (1994).

[12] Nuclear-21.Net/NucInfo, private communication, courtesy of Luc Van Den Durpel.

[13] Data taken from: *Uranium 2014: Resources, Production and Demand*, OECD Nuclear Energy Agency and the International Atomic Energy Agency.

[14] Taking the mass of the Earth's crust to be 2.37×1022 kg and the abundance of thorium as 0.0006% gives a mass of thorium in the Earth's crust of 1.4×1014 tons.

[15] Rubbia, C., A Future for Thorium Power? in *Thorium Energy for the World*, ThEC13 Proc., CERN

Globe of Science and Innovation, Geneva, Switzerland (October 27-31, 2013), Springer, Berlin (2016).

[16] Revol, J.-P., Accelerator-Driven Systems (ADS) Physics and Motivation, in *Thorium Energy for the World*, ThEC13 Proc., CERN Globe of Science and Innovation, Geneva, Switzerland (October 27-31, 2013), Springer, Berlin (2016).

[17] Vijayan, P.K., Overview of the Thorium Program in India, in *Thorium Energy for the World*, ThEC13 Proc., CERN Globe of Science and Innovation, Geneva, Switzerland (October 27-31, 2013), Springer, Berlin (2016).

[18] Kadak, A.C., A Future for Nuclear Energy: Pebble-Bed Reactors, *Int. J. Critical Infrastructures*, *1*(4), 330-345 (2005).

[19] Merle-Lucotte, E., Introduction to the Physics of Thorium Molten Salt Fast Reactor (MSFR) Concepts, in *Thorium Energy for the World*, ThEC13 Proc., CERN Globe of Science and Innovation, Geneva, Switzerland (October 27-31, 2013), Springer, Berlin (2016).

[20] Feinberg, S. M., Discussion Comment, Rec. of Proc. Session B-10, ICPUAE, United Nations, Geneva, Switzerland (1958); Driscoll, M.J., Atefi, B., Lanning, D.D., *An Evaluation of the Breed/Burn Fast Reactor Concept*, MITNE-229 (December 1979); Feoktistov, L.P., *An Analysis of a Concept of a Physically Safe Reactor*, Preprint IAE-4605/4, in Russian (1988); Teller, E., Ishikawa, M., Wood, L., Completely Automated Nuclear Reactors for Long-Term Operation (Part I), *Proc. of the Frontiers in Physics Symposium*, American Physical Society and the American Association of Physics Teachers Texas Meeting, Lubbock, Texas, USA (1995).

[21] Takahashi, H., Yang, Y., Yu, A., *An Accelerator-Driven Reactor for Meeting Future Energy Demand*, BNL 44967, IAEA Technical Committee Meeting on the Feasibility and Motivation for Hybrid Concepts for Nuclear Energy and Transmutation, Madrid, Spain (September 17-19, 1997).

[22] Bowman, C. D., Accelerator-Driven Systems for Nuclear Waste Transmutation, *Annu. Rev. Nucl. Part. Sci. 48*, 505-556 (1998).

[23] FEAT Experiment: Andriamonje, S., et al., *Phys. Lett. B 348*, 697-709 (1995).

[24] TARC Experiment: Abánades, A., et al., Nucl. Instrum. *Methods Phys. Res. A 478*, 577–730 (2002).

[25] The CERN n_TOF facility: Gunsing, F., Nuclear Data for the Thorium Fuel Cycle and Transmutation, in *Thorium Energy for the World*, ThEC13 Proc., CERN Globe of Science and Innovation, Geneva, Switzerland (October 27-31, 2013), Springer, Berlin (2016).

[26] ENDB/B-VII.1, *Nuclear Data Sheets*, Vol. 112, Issue 12, December 2011, data processing courtesy of Federico Carminati, CERN.

[27] Grillenberger, J., Seidel, M., High Intensity Proton Beam Production with Cyclotrons, *Proc. of the Workshop Applications of High-Intensity Proton Accelerators*, Raja, R. (ed.), World Scientific, Singapore (2010).

[28] Latgé, C., MEGAPIE: The World's First High-Power Liquid Metal Spallation Neutron Source, in *Thorium Energy for the World*, ThEC13 Proc., CERN Globe of Science and Innovation, Geneva, Switzerland (October 27-31, 2013), Springer, Berlin (2016).

[29] SNS, see, for instance: http://neutrons.ornl.gov/sns.

[30] ESS Technical Design Report, ESS-0016915 TDR Printed Revi-

sion (April 23, 2013) ESS-doc-274, http://europeanspallationsource.se/documentation/tdr.pdf.

[31] Cornell, J., Blumenfeld, Y., Fortuna, G., Final Report of the EURISOL Design Study (2005-2009), *A Design Study for a European Isotope-Separation-On-Line Radioactive Ion Beam Facility*, HAL Id: in2p3-00462950 (March 10, 2010) http://hal.in2p3.fr/in2p3-00462950.

[32] Aït Abderrahim, H., MYRRHA: A Flexible and Fast Spectrum Irradiation Facility, in *Thorium Energy for the World*, ThEC13 Proc., CERN Globe of Science and Innovation, Geneva, Switzerland (October 27-31, 2013), Springer, Berlin (2016).

[33] Luo, P., Wang, S.-C., Hu, Z.-G., Xu, H.-S., Zhan, W.-L., Accelerator-Driven Subcritical Systems – A Promising Solution for Cycling Nuclear Fuel, *Physics*, *45*(9), 569-577 (2016), DOI: 10.7693/wl20160903.

[34] HISPA or High Intensity Superconducting Proton Accelerator, Bhabha Atomic Research Center, Mumbai, India.

[35] Zelinsky, A.Y., et al., NSC KIPT Neutron Source on the Base of Subcritical Assembly Driven with Electron Linear Accelerator, *Proc. of IPAC2013*, Shanghai, China, THPFI080 (January 2013).

[36] Sasa, T., The Japanese Thorium Program, in *Thorium Energy for the World*, ThEC13 Proc., CERN Globe of Science and Innovation, Geneva, Switzerland (October 27-31, 2013), Springer, Berlin (2016).

[37] iThEC's Web page: http://www.ithec.org.

[38] Sidorkin, S.F., Rogov, A.D., Ponomarev, L.I., Koptelov, E.A., Proposal of the ADS Research Stand Based on the Linac of the Institute for Nuclear Research of the Russian Academy of Sciences, in *Thorium Energy for the World*, ThEC13 Proc., CERN Globe of Science and Innovation, Geneva, Switzerland (October 27-31, 2013), Springer, Berlin (2016).

[39] EU CALL: FET-OPEN – *Novel Ideas for Radically New Technologies*, Call identifier: H2020-FETOPEN-2016-2017, Publication date: October 14, 2015.

[40] ENEA: Italian national agency for new technologies, energy, and sustainable economic development, 76 Lungotevere Thaon di Revel, 00196 Rome, Italy.

[41] Conjat, M., Mandrillon, J., Mandrillon, P., Cyclotron Drivers for Accelerator-Driven Systems, AIMA DEVELOPPEMENT Company, in *Thorium Energy for the World*, ThEC13 Proc., CERN Globe of Science and Innovation, Geneva, Switzerland (October 27-31, 2013), Springer, Berlin (2016).

Efficient Use of Electrical Power in the Context of Sustainability

William D. Phillips and Gerald FitzPatrick

This paper is based on an oral presentation made by Academician W.D. Phillips at the Plenary session of the Pontifical Academy of Science, which met at the Vatican during 25-29 November 2016. The material here is informed by work at the US National Institute of Standards and Technology (NIST) on the electrical power grid in the United States. We are grateful for input to this paper from our NIST colleagues, Allen Goldstein, Thomas Nelson and Gerard Stenbakken.

While the title of this paper is "Efficient use of electrical power", in keeping with the theme of the plenary session *Science and Sustainability*, in fact, the paper is about the "Smart Grid". The idea is that to meet the needs of a future in which electricity is generated by sources throughout both transmission and distribution grids and used in a sustainable manner, we will need a flexible and responsive replacement for the existing infrastructure – that is the Smart Grid [1, 2].

Today, electricity in the US is, for the most part, distributed by the "legacy" electric power grid, the system that was developed during the over 120 years that preceded the idea of a Smart Grid [3]. In the legacy grid, electricity is generated in big, static generating plants. Those plants produce alternating current, transform the voltage up to very high voltage to minimize energy losses over long distance transmission grids, and then, at the customer level, they transform it down in distribution grids to a voltage that depends on the customer: whether it is a big or a medium or residential size customer. A key feature of the legacy grid is that it provides a one-way process (which is something that Steve Chu emphasized in his talk, where he mentioned the legacy system): You make electricity in big static power plants and you deliver it to the customer.

The idea of the Smart Grid is to do lots of things that go beyond the static and one-way paradigm of the legacy grid. One feature is to have a much more diverse system where users may in fact be generating electricity by a variety of means. For example, residential users might be generating electricity from solar panels installed on their home. Bigger installations, like factories and apartment buildings and offices, might be generating electricity for use locally, for example in microgrids as Steve Chu mentioned, and also sending it back into the larger grid. Microgrids, which are self-sustaining and can operate for limited periods when the larger grid suffers a power outage, may become more prevalent as renewable resources such as solar, wind, and battery storage for electrical energy get increasingly higher penetration into electrical distribution systems [4].

In order to achieve the desired benefits of a variety of sources of generated electricity, one needs to have energy storage. As we have heard, batteries are getting better all the time, so we hope that batteries will be an increasingly important and efficient part of the energy storage landscape. We heard from Steve Chu about pumping water into elevated tanks as an energy storage strategy, and find this appealing. During our youth, many farms in the United States had windmills, which looked just like the picture that Steve showed, pumping water to store energy. It was a good idea then, and it is satisfying to know that it remains a good idea today. Of course, we have heard that there are lots of other ways to store energy. For example, batteries are an essential part of plug-in and hybrid electric vehicles that may play a role in energy storage in the grid of the future [2]. One can also use electricity to make fuels for later consumption. While the details of energy storage are important, these are not the focus of this presentation.

An important feature of the Smart Grid is that it will be more of a web than a radial arrangement. The legacy grid is mainly radial, with centralized generation, radial distribution, and a relatively static structure. A good feature of such a system is that one can predict its behavior. By contrast, in the future we will be better able to control and adapt to changing electric system behavior by using smart grid systems. We hope to have a high penetration of renewable sources, and a lot of those renewable sources are going to be variable. For example, when the wind blows, you generate electrical power, and when it doesn't, you don't. When the sun shines, you generate electrical power and when it doesn't, you don't. We also expect a high penetration of variable loads, for example electric vehicles. If everyone has an electric vehicle and they all come home at 5:30 and plug them in, that will produce a big jump in the demand for electricity that is different from what we experience today [3]. This dynamic nature of generation and demand is going to make things a lot more complicated.

The difficulties with that kind of a system are akin to the difficulty of predicting the way in which some sort of a neural network might work, a complex problem that presents significant challenges. As one illustration of the kind of challenge that might become more prevalent in the future, consider an incident from a few years ago when a power plant in Florida went off line. In a matter of seconds, the disturbance from that incident spread throughout the entire eastern part of the United Sates [5]. The grid needs to be able to respond to incidents like this within seconds and incidents like this are likely to happen more and more frequently as we transition to a less static electrical grid structure.

An important contributor to the dynamic nature of the grid is weather. We have been seeing a near-linear increase in the kind of weather-related events that cause power outages, and this has resulted in significant costs, measured in billions of US dollars per year. An important connection to sustainability is that a lot of people believe that this increase in weather-related events is due to climate change and that it is going to get worse if we as a world community don't transition to a more sustainable energy economy. Furthermore, weather-related events become more and more of an issue the more complex the grid becomes, and the grid must become more complex in order, at least in part, to handle all of the renewable resources.

To build a Smart Grid that can respond to an increasingly dynamic environment, whether the dynamics come from variable generation, variable demand, weather events, or whatever, we need real-time information about what is happening. This is where NIST, as a metrology laboratory, comes in: reliable and useful information derived from accurate measurement.

Among the things we need to know about the grid are the amplitude and phase of the electric current and voltage at a lot of different places. Furthermore, we need to know these parameters in real time. Here, the capabilities of a National Metrology Institute like NIST are crucial. At NIST we know how to measure electrical parameters, and we know how to time-stamp them so that everybody who receives this information is able to know exactly what's happening simultaneously over the entire grid. This is, of course, not the only information that is needed, but having this information is one of the requirements to do what we want to do with a Smart Grid.

As an example of how a metrology laboratory can improve the capabilities needed to operate a Smart Grid, consider the case of a certain model of a Phasor Measurement Unit (PMU) [6]. These units measure, among other things, the current, voltage, frequency, and rate of change of frequency at locations throughout the grid, reporting those parameters and the time of the measurement. These data can be used by the Energy Management Systems that determine electric power system states and power flows, and control the grid. NIST measurements showed that some of the measured parameters varied from the true values by nearly 15%, exceeding by far the specified limits for PMUs [7]. Identifying these difficulties allowed the manufacturer to make modifications that brought the typical accuracy errors of the PMUs to better than the required 1%. Getting this kind of high quality data is one of the essential requirements for the operation of a Smart Grid.

As mentioned earlier, a feature of a more sustainable future is that there are going to be microgrids: local communities will have their own grids; they will produce electricity; they will use it internally; they will sell it back to the larger grid. This will create both opportunities and challenges. Renewable sources, sustainable but variable-demand end-use, microgrids, and other features beneficial to a sustainable future will be easier to integrate into to our general electrical power system, if we have the kind of intelligence in our Smart Grid that is both measurement and response. I've only spoken about measurement in detail, but obviously response is equally important. As Steve Chu indicated, we need things like machine learning to figure out how to respond to the kinds of changes that a future Smart Grid is going to experience.

We end with this thought: that the instrumentation for the Smart Grid, and the reliable measurements from that instrumentation, areas in which metrology laboratories like NIST excel, are among many technological developments that we need for a sustainable energy economy.

References

[1] *NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 3.0*, NIST Special Publication 1108r3, available for download at https://www.nist.gov/sites/default/files/documents/smartgrid/NIST-SP-1108r3.pdf

[2] The Smart Grid: An Introduction, prepared for the US Department of Energy by Litos Strategic Communication under contract No. DE-AC26-04NT41817, Subtask 560.01.04 available for download at: https://energy.gov/oe/downloads/smart-grid-introduction-0

[3] *United States Electricity Industry Primer*, Office of Electricity Delivery and Energy Reliability U.S. Department of Energy DOE/OE-0017 available for download at https://www.energy.gov/indianenergy/downloads/united-states-electricity-industry-primer

[4] How Microgrids Work, US Department of Energy, see description at https://energy.gov/articles/how-microgrids-work (2014)

[5] Florida Blackout 2008, frequency disturbance propagation in Eastern Interconnection of the US Power Grid as observed using FNET. See video at https://www.youtube.com/watch?v=H7y-oJYpDkM. For further information on FNET see website: http://fnetpublic.utk.edu/

[6] Stenbakken, Gerard N. and Zhou, Ming,

Dynamic Phasor Measurement Unit Test System, Proceedings of the IEEE Power and Energy Society General Meeting, Tampa, FL, July 2007, available for download at https://www.nist.gov/sites/default/files/documents/smartgrid/DynamicPMUTestSys0607.pdf

[7] Goldstein, Allen R., *2014 NIST Assessment of Phasor Measurement Unit Performance*, NISTIR 8106, Gaithersburg, MD, Feb 2016, available for download at https://www.nist.gov/publications/2014-nist-assessment-phasor-measurement-unit-performance

PHYSICS SESSION

Fight or Flight – A Tale of Two Disruptions

Hans Joachim Schellnhuber, Gitta Köllner, Maria Martin

To be, or not to be, that is the question:
Whether 'tis nobler in the mind to suffer
The slings and arrows of outrageous fortune,
Or to take arms against a sea of troubles,
And by opposing, end them? To die: to sleep

William Shakespeare
The tragedy of Hamlet, Prince of Denmark
(Act 3, Scene 1)

While Hamlet famously vacillates between suffering the rough sides of life and taking the courage to end it, humanity as a whole is currently facing a similar existential choice. However, what Hamlet does not actually have in mind is the third option: to take arms against a sea of troubles and fight against his outrageous fortune. There are sayings and quotes for every situation. In the case of humanity, it is time to recognise that we are architects of our own fates.

Ruling out intentional self-destruction, humanity – like Hamlet – faces a crossroads: To flee or to fight. There is imminent danger associated with anthropogenic climate change. And since we have wasted decades in analysing the situation without taking noteworthy action, we are intellectually more than well prepared to take a decision. We know the risks of both choices: On the one hand, fighting climate change will involve some serious scratches. Fleeing this fight, on the other hand, will allow more and more devastating climate impacts to catch up with us, until we will reach a state indistinguishable from intentional self-destruction.

A tale of two disruptions describes humanity's current situation. Either we take up the proverbial arms and transform our society in an effort that is comparable in its immensity to times of war, or we will be transformed by the results of our inability or unwillingness to combat climate change.

What we see in terms of extreme events is just a foretaste of what lies ahead if we continue along the still unbroken path of carbon-based lifestyles at the expense of the world's poor and future generations. The unprecedented dimension and frequency of extreme weather events during the last two years give a glimpse of the world to come.

A Sea of Troubles

In the summer of 2018, heatwaves in North America, Western Europe, the Caspian Sea region and Siberia, which affected important bread-basket regions for food production, coincided with heavy rainfall in South-East Europe and Japan (Kornhuber et al. 2019). Events like these trickle into the public's consciousness. It is but consequences for our everyday lives that make an abstract concept like climate truly manifest. One striking example of change in the highly complex atmosphere-ocean system translating directly into people's daily routine is the meandering jet stream in the high Northern latitudes. At an altitude of eleven kilometres, this band of winds tends to form ever-bigger waves if the temperature gradient between the polar region and the temperate latitudes decreases (Figure 1). These so-called Rossby waves can overlap so the jet stops propagating for several weeks due to subtle resonance phenomena (Petoukhov et al. 2013). The longer we observe the associated wave pattern, the clearer it becomes that this phenomenon has occurred more often over recent years. In other words, extreme weather patterns last longer – so a couple of nice, warm days become a heatwave, and some refreshing rainy ones turn into a deluge (Kornhuber et al. 2019).

As the global concentration of greenhouse gas emissions is still on the rise, as air and ocean temperatures are steadily increasing, the impacts of planetary warming become more and more apparent. Heatwaves and

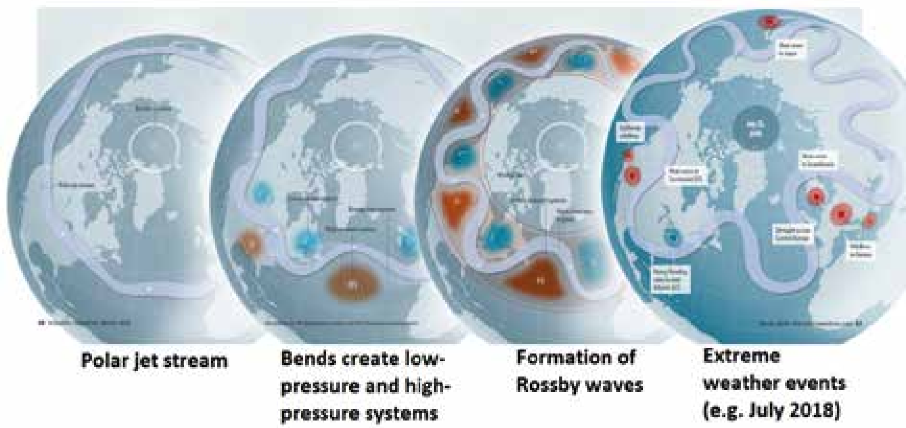


Figure 1. Formation of Rossby waves in the polar jet stream causing extreme weather events in the Northern hemisphere, fostered through resonance phenomena (Source: Pethoukov et al., PNAS, 2013 Graphic: Mann, M., Scientific American, 2019).

droughts call for better planning in the agricultural sector, as well as in health systems. Weather extremes can exacerbate food insecurity, social unrest and conflict in affected regions. Tropical cyclones impact a growing number of people directly and harm economies where they make landfall (Winston and Zemyla 2019). The devastating cyclone Idai, for example, was one of the most deleterious ever in the Southern hemisphere in terms of deaths and the number of people stricken (Warren 2019). Other prominent examples are the raging bushfires in California and Australia, unprecedented in frequency and intensity, following droughts and extremely hot summers (Winston and Zemyla 2019).

But there are more examples of looming risks, particularly those associated with tipping elements in the Earth System, which may be triggered to flip irreversibly into a different state once a certain temperature threshold is crossed. Some of these elements could already be tipped within the temperature range of 1.5-2°C, i.e. within the Paris Agreement corridor (see Figure 2). Even more critical thresholds or tipping points are approached if we proceed along our current path of emissions, heading towards a largely unknown future (Schellnhuber, Rahmstorf, and Winkelmann 2016) (*for more detail please see the contribution of Schellnhuber & Martin 2014 in "Sustainable Humanity, Sustainable Nature: Our Responsibility"*, Pontifical Academy of Sciences, Extra Series 41, Vatican City, 2015).

Temperatures alone cover only one dimension of tipping dynamics. For instance, the Amazon rainforest is of global climate relevance and a very sensitive ecosystem. Its life-supporting hydrological cycle is prone to disruption with increasing temperatures and forest-cover loss, which could lead to a shift to savanna vegetation and a decrease in precipitation followed by prolonged dry-seasons. Synergies between warming temperatures, deforestation and clearance fires could lower that threshold of tipping to mere 20-25% forest cover loss (Lovejoy and Nobre 2018). In such complex systems, multi-layered interactions can bring us faster to exceed the thresholds and, in some cases, to a point of no return. Acting in a precautionary manner becomes imperative, especially when uncertainties are involved.

Standing at a crossroads, one needs to take a decision. But how? In the end, it comes down to weighing the trade-offs between anticipated benefits and damages in the broadest sense. However, our evolutionary heritage has not endowed us with a particular talent to factor in long-term risks – this is challenge number one. Challenge number two is further complicating the decision process: Climate-related risks are usually not distributed in the typical bell-shaped Gaussian (normal) distribution, but

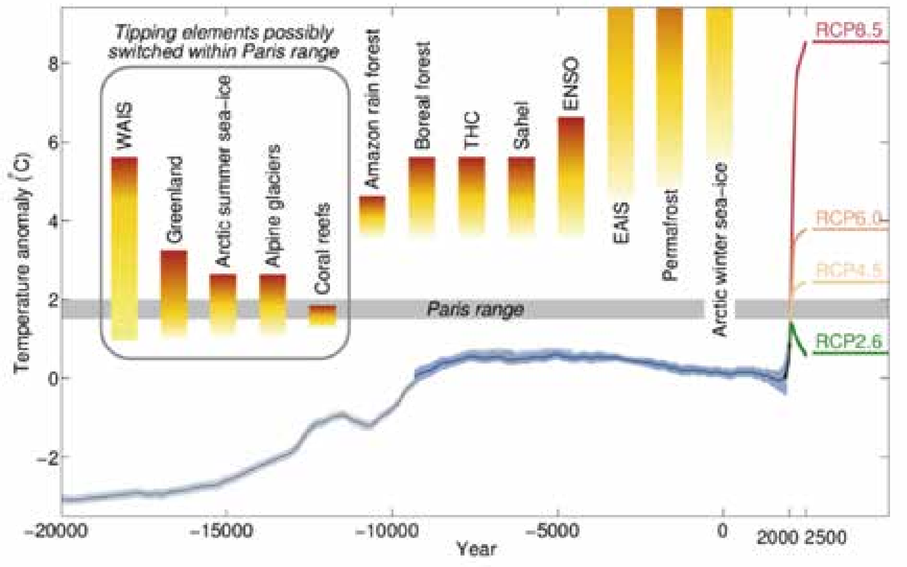


Figure 2. Tipping elements in the context of global mean temperature change (West Antarctic Ice Sheet (WAIS); thermohaline circulation (THC); El Niño-Southern Oscillation (ENSO); East Antarctic Ice Sheet (EAIS). Shown is the global-mean surface temperature development from the Last Glacial Maximum through the Holocene, based on palaeoclimatic proxy data as the grey and light blue lines, with the blue shading showing one standard deviation), instrumental measurements since 1750 ad (HadCRUT data, black line) and different global warming scenarios for the future. Threshold ranges for crossing various tipping points, where major subsystems of the climate system are destabilized, are indicated by gradient from yellow to red bars for each tipping element. Coral reefs are likely to reach tipping point within the range of the Paris Agreement (Source: Schellnhuber et al., 2016, Nature Climate Change).

are characterized by "fat tails" (Weitzman 2014). This means that statistical "outliers", extremes that are very different from the norm, are more likely than usually expected. We, however, intuitively perceive them as less likely to happen, due to our everyday experience with normal distributions (like the outcome of a lottery game). This partial blindness of humanity is particularly dangerous.

Projections of global warming are prominent illustrations of a fat-tailed distribution. Accelerated and runaway warming is not the most likely event, but it would have impacts beyond imagination. Since we define risk as the product of likelihood multiplied by impact, impactful outliers at the fringe of the probability distribution pose an existential risk to civilization. Although it appears counterintuitive, we have to factor them into the decision process on which path to take and act accordingly. On a global scale, warming around 4°C would not allow us to preserve our societal structures of today. Ecosystems would cascade into decay and no longer support human societies adequately, and violent conflicts are likely to arise more frequently (Spratt, Dunlop, and Barrie 2019).

Going down the business-as-usual path, we will reach tipping points in the Earth System, even some irreversible ones. Leading the way to self-reinforcing biogeophysical feedbacks, tipping cascades across elements of the cryosphere, the biosphere and global circulation patterns could very well change the face of the planet – transforming it to a Hothouse Earth without the possibility for return (Steffen et al. 2018).

Tipping cascades strung around the planet threaten the conditions we live in. For example, the decrease of Arctic sea ice further warms the region due to albedo feedbacks and thus causes accelerated melting of the Greenland ice sheet. This inserts freshwater into the North Atlantic Ocean, potentially slowing down the Atlantic Meridional Overturning Circulation (Lenton et al. 2019). Observations suggest that a slowdown of 15% since the 1950s has already happened (Caesar et al. 2018). The global heat transport through the ocean by the Gulf Stream might affect the West African monsoon negatively and generate severe droughts in the Sahel region. Another consequence could be the drying of the Amazon rainforest, which could trigger a shift to savanna vegetation. As a consequence, heat building up in the Southern Ocean might reinforce the pace of Antarctic ice loss (Lenton et al. 2019).

The urgency of the situation into which humanity has navigated itself calls for rapid action and behavioural change. Unfortunately, it is not that simple, since humans are creatures of habit. For example, the perception of the link between extreme weather events and human interference with the climate system is highly dependent on the individual attribution of those extremes. It varies greatly due to political beliefs, loyalties and social norms (Ogunbode et al. 2019). Heterogeneity of societies and individuals can be seen as a hurdle, which needs to be overcome for behavioural change. Simultaneously, diversity can offer opportunities for innovation and cooperation in tackling the climate crisis, especially in adapting and scaling solutions down to a regional context. Tackling the challenge from all possible angles, politically, economically, institutionally and socially, might yield the highest success rate. Perhaps one such focus in this context is on socioeconomic "tipping" points and processes, as discussed in a recent study (Otto et al. 2020).

Fight or Flight

Which path are we going to take at this crossroads? The evolutionary options for individuals and collectives, when confronted with a life-threatening situation, are to fight, to flee or to freeze. Inaction of governments and lack of political will, especially in the developed countries in the global North, has actually procrastinated adequate action on climate change mitigation and adaptation for more than 30 years. We need to switch to fighting mode now. It requires courage and resolve to embark on a deliberate transformation. However, it is the only sensible option in order to avoid the by far more devastating uncontrolled transformation imposed upon us by a disruptively changing climate.

The degree of bravery needed, however, has increased over time through our unwillingness to take action, and is quickly approaching the border to bravado. Thorough assessments of our remaining options to hold the 1.5°C line reveal them crumbling to almost nothing when unrealistic pathways are one by one excluded. There simply is no good answer to the 1.5°C question! In most models, emission pathways include massive carbon dioxide removal (CDR) from the atmosphere to achieve climate stabilization. Yet in reality, the technologies available for capturing and storing carbon, either geologically or on managed land, have not evolved to a level that meets the performance targets of the models so far. Efficiency and scale lag far behind the projected timeline of decarbonisation pathways.

The question remains: What does the necessary action look like, from the political, economic, and individual perspective? Everything that is not physically or ethically impossible is a moral imperative. Fortunately, there are numerous studies and a vast variety of science-based suggestions. One of the biggest efforts will be the decarbonisation of the global economies. This appears to be a tremendously vague undertaking, but bright minds have broken theoretical concepts down to feasible, step-by-step programs. Roadmaps for countries and sectors can be particularly useful tools, since they act as planning instruments bridging short-term goals with long-term strategies. Rockström et al. (2017) highlight the decade from 2020 to 2030 as the base from which to launch rapid decarbonisation. In their scenario, carbon dioxide emissions should peak no later than 2020 in view of the Paris Agreement. Options for kicking off the transformational processes are manifold: carbon tax schemes, cap-and-trade systems, feed-in tariffs or polycentric power grids are viable schemes. Certainly, human behaviour plays an enormous role. Behavioural change has the reputation of evolving slowly and not being predictable. Nevertheless, disruptive, innovative change provoked by collective human behaviour has happened throughout history and bears the potential to achieve ambitious goals in the near future. We should channel this capacity into bold action for building a resilient future (Rockström et al. 2017). The defining decade for serious climate action has begun.

Planetary Emergency

The probability that - even if all national pledges in the context of the Paris Agreement were implemented completely - global warming could reach 3°C (or more) at the end of this century is unfortunately very high. Pledges are not on track to achieve the emission reductions they are supposed to. In order to avoid catastrophic impacts, the slow-down of heating should start as soon as possible. It is a simple rule: the lower the warming, the better.

The goal of staying well below 2°C, preferably not exceeding 1.5°C of warming compared to pre-industrial levels (IPCC 2018), actually places us in an emergency situation. The status of emergency mirrors the high risk of severe consequences of inaction and the urgency of a timely solution. The factors setting the stage are the intervention time and the reaction time – or, more precisely, their relationship: If the reaction time of tackling climate change is longer than the intervention time, there is no time left to manoeuver – we have lost control (see Box: Lenton et al. 2019).

Moreover, it has to be stated repeatedly that the challenge is immense: The tipping of one element in the Earth system can increase the probability of tipping another element significantly – tipping cascades of biogeophysical elements can be triggered. Such an existential threat to societies worldwide clearly defines an emergency situation, which requires an emergency response. We need to consider where future tipping points may lie and what other tipping elements will possibly emerge. Further monitoring, quantification and model-

EMERGENCY: DO THE MATHS

We define emergency **E** as the product of risk and urgency. Insurers define risk **R** as probability **p** multiplied by damage **D**. Urgency **U** is defined in emergency situations as reaction time to an alert τ divided by the intervention time left to avoid a bad outcome **T**. Thus:

$$E = R * U = p * D * \frac{\tau}{T}$$

The situation is an emergency if both risk and urgency are high. If reaction time is longer that the intervention time left ($\frac{\tau}{T} > 1$), we have lost control (Lenton et al. 2019).

ling is vital for fostering our understanding of the hyper-complex situation we live in (Lenton et al. 2019).

Continuing on the path of 'business as usual' means risking chaotic and disruptive changes accompanied by conflict and violence on a global scale. Proactive measures are the way to choose, instead of a sheer responsive reaction to an emergency: Fight and not flee. It is time to seize the opportunity of momentum provoked by the fierce and persistent protests by young people around the world. The question Hamlet poses only leaves one conclusive and coherent answer when considering the current global situation, namely to behave like a connected global society, taking arms against a sea of troubles (and literally against rising sea levels). A happy ending of this tale of two disruptions is still possible.

Bibliography

Caesar, L., S. Rahmstorf, A. Robinson, G. Feulner, and V. Saba. 2018. "Observed Fingerprint of a Weakening Atlantic Ocean Overturning Circulation". *Nature.* https://doi.org/10.1038/s41586-018-0006-5

IPCC. 2018. "Proposed Outline of the Special Report in 2018 on the Impacts of Global Warming of 1.5° C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways , in the Context of Strengthening the Global Response to the Threat of Climate Change". *Ipcc – Sr15* 2 (October): 17-20. www.environmentalgraphiti.org

Kornhuber, Kai, Scott Osprey, Dim Coumou, Stefan Petri, Vladimir Petoukhov, Stefan Rahmstorf, and Lesley Gray. 2019. "Extreme Weather Events in Early Summer 2018 Connected by a Recurrent Hemispheric Wave-7 Pattern". *Environmental Research Letters* 14 (5): 054002. https://doi.org/10.1088/1748-9326/ab13bf

Lenton, Timothy, Johan Rockström, Owen Gaffney, Stefan Rahmstorf, Katherine Richardson, Will Steffen, and Hans Joachim Shellnhuber. 2019. "Climate Tipping Points – Too Risky to Bet Against". *Nature* 575: 592-95.

Lovejoy, Thomas E., and Carlos Nobre. 2018. "Amazon Tipping Point". *Science Advances* 4 (2): 1-2. https://doi.org/10.1126/sciadv.aat2340

Ogunbode, Charles A., Christina Demski, Stuart B. Capstick, and Robert G. Sposato. 2019. "Attribution Matters: Revisiting the Link between Extreme Weather Experience and Climate Change Mitigation Responses". *Global Environmental Change* 54 (November 2018): 31-39. https://doi.org/10.1016/j.gloenvcha.2018.11.005

Otto, Ilona M., Jonathan F. Donges, Roger Cremades, Avit Bhowmik, Richard J. Hewitt, Wolfgang Lucht, Johan Rockström, et al. 2020. "Social Tipping Dynamics for Stabilizing Earth's Climate by 2050". *Proceedings of the National Academy of Sciences*, January, 201900577. https://doi.org/10.1073/pnas.1900577117

Petoukhov, Vladimir, Stefan Rahmstorf, Stefan Petri, and Hans-Joachim Joachim Schellnhuber. 2013. "Quasiresonant Amplification of Planetary Waves and Recent Northern Hemisphere Weather Extremes". *Proceedings of the National Academy of Sciences* 110 (14): 5336-41. https://doi.org/10.1073/pnas.1222000110

Rockström, Johan, Owen Gaffney, Joeri Rogelj, Malte Meinshausen, Nebojsa

Nakicenovic, and Hans Joachim Schellnhuber. 2017. "A Roadmap for Rapid Decarbonization". *Science* 355 (6331): 1269-71. https://doi.org/10.1126/science.aah3443

Schellnhuber, Hans Joachim, Stefan Rahmstorf, and Ricarda Winkelmann. 2016. "Why the Right Climate Target Was Agreed in Paris". *Nature Climate Change* 6 (7): 649-53. https://doi.org/10.1038/nclimate3013

Spratt, David, Ian Dunlop, and Admiral Chris Barrie. 2019. "Existential Climate-Related Security Risk: A Scenario Approach", May.

Steffen, Will, Johan Rockström, Katherine Richardson, Timothy M. Lenton, Carl Folke, Diana Liverman, Colin P. Summerhayes, et al. 2018. "Trajectories of the Earth System in the Anthropocene". *Proceedings of the National Academy of Sciences of the United States of America*. https://doi.org/10.1073/pnas.1810141115

Warren, Matthew. 2019. "Why Cyclone Idai Is One of the Southern Hemisphere's Most Devastating Storms". *Nature*. https://doi.org/10.1038/d41586-019-00981-6

Weitzman, Martin L. 2014. "Fat Tails and the Social Cost of Carbon". In *American Economic Review*, 104:544-46. American Economic Association. https://doi.org/10.1257/aer.104.5.544

Winston, Cyclone, and Novaya Zemyla. 2019. *WMO Provisional Statement on the Status of the Global Climate in 2019.* Vol. 1961.

SPECIAL SESSION

Food & Nutrition – The Role of Biotechnology in Agriculture

(Joachim von Braun and Ingo Potrykus)

Introduction to the Special Session on Food & Nutrition – The Role of Biotechnology in Agriculture

Ingo Potrykus

Welcome to the Special Session on Food & Nutrition – The Role of Biotechnology in Agriculture.

The Academy invited me to organise a Symposium on these lines. With 800 million starving, an expected increase in the world population to 9.9 billion before 2050, the expectation that agriculture has to produce 70% more food while protecting the environment against the additional limitations arising from climate change, this is a timely and pressing topic.

Scientists are virtually unanimous in their conclusion that products from GM crops have great potential to contribute to food and nutrition security and are safe, based on both theory and observation. Influential NGOs, members of the public and media outlets argue – based on emotions and a hidden agenda – that GM-crops are useless and too risky to both the environment and the consumer and, therefore, should be banned.

We meet today to discuss in this context the potential of agro-biotechnology, especially genetic engineering. What has it contributed so far, especially to food and nutrition security of poor and disadvantaged populations in developing countries? And even more important, what hurdles prevent an even more effective contribution?

To this end we have been able to attract an outstanding group of experts and I am grateful that they all responded positively to the invitation despite the fact we could offer them only fifteen minutes for the presentations and five minutes for discussion.

There is Professor Joachim von Braun, former Director General of the International Food Policy Research Institute, Washington, who will remind us of the need for continued and sustained improvements of the food system.

There is Professor Peter Beyer, my partner in the Golden Rice project, who has expended his research to the topic of yield improvement and has most impressive data on yield increase with GM-rice and will discuss the GMO potential.

There is Dr. Howarth Bouis, who just received the World Food Prize for his demonstration that "biofortification" – the use of genetics to improve the nutritional content of crop plants – can indeed improve the nutritional status of poor populations in developing countries.

There is Professor Peter Raven, outstanding plant ecologist and former director of the Missouri Botanical Garden and named "Hero of the Planet" by TIME Magazine for his work. Peter will tell us how biodiversity can benefit from genetic engineering.

There is Dr. Mariano Bosch, Vice President of the National Institute of Agricultural Technology (INTA) Argentina, who will inform us on the real benefits to Argentine economy and ecology from no-till agriculture, based on herbicide-resistant GM-soybeans.

There is Professor Matin Qaim, agro-economist from the University of Göttingen, who for decades has been analysing and publishing the effects of GMOs on poor rural communities in developing countries. Matin will speak about the socio-economic impacts of genetic engineering technology.

There is Professor Marc van Montagu, World Food Prize laureate from 2014, the co-inventor of traditional, *Agrobacterium tumefaciens-based* genetic engineering technology, and tireless advocate and promoter for the use of this technology to the benefit of the poor and disadvantaged. Marc will highlight the contributions of the public sector to technology development.

There is Dr. Adrian Dubock, architect of the public-private-partnership of the Humanitarian Golden Rice project for development and deployment of Golden Rice, who is advancing the project against all hurdles preventing, so far, the use of this life-saving invention. Adrian will describe his experience in advancing this public sector GMO-project for public good – against the massive obstruction by NGOs, and under respecting all rules and regulations which all work with GMOs has to follow.

And there is Sir Rich Roberts, Nobel Laureate in Physiology and Medicine 1993, who finds it difficult to tolerate the anti-scientific ideology and political opportunity that blocks genetic engineering technology with plants and the Golden Rice project. Sir Richard has organized an appeal to "Greenpeace, the United Nations and Governments around the world", signed so far by 121 Nobel laureates and 6319 scientists. Sir Richard will present this project for which he hopes to also find support from world religious leaders.

The Need for Accelerated and Sustained Improvements in Food and Nutrition of the Poor

Joachim von Braun

1. Introduction – Changing Contexts

Fundamental forces of societal and economic change must be considered when searching and advocating technological and institutional innovations to reduce misery and hunger in the unequal world, where science is dominated by wealthy countries. Secular decline in economic growth (in terms of GDP) and possibly reduced power of innovations for growth in high-income countries (Gordon 2016), combined with growing within-country inequalities (Milanovic 2016) has far-reaching implications for changing attitudes and shape of policies. Technology pessimism and globalization skepticism is a factor in parts of the world's wealthier population segments and increases their demand for regulation to fix the status quo. To the extent these trends adversely impact science applications, such as biological sciences of developmental relevance, they adversely affect innovation serving advances of food and nutrition security of the poor. This certainly raises ethical considerations related to the poor today and to future generations, both of which have not much voice in present discourses.

The present food and nutrition problems need to be addressed while future challenges must be considered, too. Due to constraints of natural resources, and due to economic constraints of low-income people, innovations are central to facilitate access to improved nutrition. Innovations are technological and institutional and both are interrelated. Affordability of healthy and nutritious food is critical for low-income households. Technology's role should be viewed in a broad context of action areas for improved nutrition, i.e. together with access to markets, to services, and to income opportunities, all of which are determinants behind access to food and nutrition. Sustained improvements in nutrition must also pay attention to marginality and exclusion of the undernourished (von Braun and Gatzweiler 2014). Peoples' knowledge and behavior importantly shape demand for improved nutrition, too.

Overall, hunger is on the decline as accounted for by the Global Hunger Index (IFPRI et al. 2016), but the various features of hunger and undernutrition remain large global problems. They are most prevalent in low and middle-income countries, but also exist partly unnoticed in industrialized countries, such as the USA and the European Union. The challenge to end hunger – as called for in the Sustainable Development Goals (SDGs) – is confronted with the fact that hunger and undernutrition have become more complex. Urban hunger and undernutrition is of growing importance while most hungry people still live in emerging economies' rural areas and on small farms. Overcoming hunger relates closely to the transformation of rural areas and of small farms' productivity, and to the quality of services reaching out to them, especially health and education services, and social safety nets. Hunger in emergencies and conflict situations is a growing political and social challenge. Micronutrient deficiencies are increasingly recognized as a large food and health problem. Ending undernutrition in South Asia requires different actions than in Africa. Environmental causes of hunger such as climate change seem to be increasing.

All these complexities call for equally complex responses in policies and programs, adjusted to regional and local circumstances, yet the key roles of technological innovations should not be neglected in the portfolio to overcome food and nutrition security. New thinking about policy, institutional and organizational innovations, and technical innovations, i.e. biological, mechanical, and information technological innovations, must come together to end hunger and undernutrition. While mainly aspects of the critically important roles of biological innovations and especially plant innovations for nutritional improvement are discussed in this workshop, this paper serves to provide a background on the needs to expand and sustain improvements in food and nutrition, and positions technological innovations among the range of other actions to meet the needs. It concludes that missing out on technological opportunities would be inefficient and unfair towards the poor.

2. Outlook of Food and Nutrition Needs in the 21st Century

The world population is growing at declining rates and will approach 9.2 billion people in 2050. It is assumed to become more stable by 2070 with about 9.4 billion people and may somewhat decline by 2100 (Lutz et al. 2014). Different global population projections differ greatly with respect to outcome and ingoing assumptions. Projections that neglect the dynamics and endogenous change in fertility, migration and the role of education tend to overstate population growth.

Nevertheless, demand for food will increase substantially in the future due to a growing world population and rising per capita income. Alexandratos and Bruinsma of FAO (2012) estimate the demand for various food groups till 2050 based on the UN population projections. They predict a 46% increase in demand for grains (of which about two thirds would be for animal feeds and other non-food uses), a 76% increase in meat demand and an 89% growth in demand for oilseeds. These expansions are challenges, if they become reality. For instance, in absolute numbers a 46% increase in grains means a global increase from 2.1 to 3.0 billion tons. Yet, it will depend upon whether changes in consumption habits of middle classes come about, such as reduced consumption of feed intensively produced animal products. Behavioural change in food consumption is slow, except when people move from rural to urban areas.

The other hope is that scope to cut losses and waste of food would enhance food availability. Losses occur at different levels of the supply chain (for example during harvest, storage or processing), and waste is mainly related to consumption behavior. Rough estimations suggest that for instance in the case of cereals 35% of the production is lost or wasted in industrialized countries, and about 20% in Africa (FAO 2011). More recent estimates in some countries suggest that losses and waste are in fact probably much smaller. Postharvest losses of maize in selected African countries range around 10 to 20% without interventions and 5 to 10% with interventions (Schuster and Torero 2016), and losses in potatoes in India and Bangladesh are around 3 to 6% (Minten et al. 2016). At such low levels of waste and losses there would be less scope for efficiency gains in the food systems, and production and yield levels need to be increased further to ensure food and nutrition security at affordable prices.

A review of global food security scenarios by van Dijk and Meijerink (2014) finds that most studies only address availability and access, but not nutrition and instability aspects of food security. Overall, they find that the few scenario exercises that attempt to provide outlooks on global child malnutrition and on prevalence of undernutrition indicate for 2050 a range of 100 to 180 million children, and for the latter a decline from about 12% to about 6%. In an increasingly demand driven global food system, food security will ever more emphasize appropriate responses to new and emerging demands (Maggio et al. 2015). Scenarios of future food demands must be part of the broader scenario building about societal, economic and environmental change. Volatility and transitions of economic systems need to be considered, as partly done in the New Lens Scenarios by Shell Corp. (2013). What the future of food and nutrition security will look like clearly depends on readiness of societies to face up to the challenges, and not on predetermined trends. That also includes the willingness to enhance technological innovations and their applications.

3. Science and Innovations to Enhance Food and Nutrition

At an aggregate global level, innovations have become more and more important for improved food security. With three quarters contribution, innovation is now the biggest source of productivity growth in world agriculture. While the overall growth in productivity was maintained, inputs as well as land and water resources have scaled back. Therefore, innovations play a crucial role in ensuring the availability of food for the global population.

3.1. Comprehensive Food and Nutrition Policies

Major innovation examples from the past, such as the cooperative formations in the 1860s in Germany, the crop-innovation based "Green Revolution" in the 1970s, the innovation of conditional cash transfer schemes in Mexico and elsewhere in the 1990s, and the food fortification and supplementation programs in the past three decades show that successful innovations had two characteristics in common. First, they had technical and institutional components and gained highest level political support, and second, they entailed years of research and experimentation before scaling up was possible. Despite great contributions of each of the innovations to the reduction of hunger and food insecurity, none of them alone is a panacea to end hunger.

A broad set of public policies is required to address hunger and nutrition risks, including policies and programs directly targeted at the undernourished and programs that indirectly improve nutrition (Pinstrup-Andersen 2013). Policy actions in three priority areas are called for: (1) expand direct support for overcoming nutrition problems of children and women, (2) adopt actions that prevent health and nutrition damage to avoid long-term negative consequences, (3) take actions to prevent and mitigate food and nutrition risks at large scale, including nutrition risks that result from economic and political disruptions.

Food and nutrition policies and programs have come a long way over the past five decades toward more comprehensiveness, impact orientation, and scale (Gillespie et al. 2016). On that long way to improvement a problem was that selective paradigms dominated and guided actions for nutrition, rather than taking guidance from science more broadly into account and systematically test interventions at scale. This problem is not overcome yet. It may currently lead to approaches that focus on ever better programming based on currently favored interventions (mainly following a public health approach), rather than also factoring in technological innovations (such as micronutrient rich foods) and institutional innovations (such as measures that can drive behavioral change).

3.2. Agricultural Research Reducing Undernutrition and Hunger and Future Potentials

In the past 200 years, several major inventions for the agricultural sector had a great influence on shaping societies (Fogel 1999). Plant nutrition was dramatically changed by Justus von Liebig's discovery of essential plant nutrients in the 1840s. The increase in food safety measures was much improved by Louis Pasteur, who treated milk to stop bacterial contamination in the 1860s. It was Gregor Mendel in the 1850s who revolutionized plant breeding through genetic considerations. Norman Borlaug's work on plant breeding in the 1970s had a huge impact on the food security situation in Latin America and Asia increasing wheat and rice yields by planting high-yielding crop varieties (Gillis 2009).

Since the 1990s, advanced biology has become important in agricultural science. Scientific innovations have made significant contributions to hunger reduction and the Centers of the Consultative Group for International Agricultural Research (CGIAR) have played important roles in that respect together with national research systems of emerging economies. Still, a big gap exists between potential agricultural productivity and yields of crop and livestock between low- and high-income countries. This gap must be further addressed by new ways of cooperation, farmers' vocational training and the strengthening of extension services.

Research increasingly focuses on the goal of achieving higher and more stable yields, on the plant-microbial relations, as well as on advances in molecular and cellular processes. New forms of water saving irrigation systems will become more important. The same applies to innovations in pest and disease resistance in a post antibiotics age, such as chemical control, biological control, sterile insects breeding, and breeding for resistance. In addition, meat substitutes made from pulses or algae have become prominent on research agendas to bridge protein gaps. Demand side innovations focus on consumption and behavior change to overcome food related health problems. Consumer preferences and the willingness of consumers to alter these will be one of the major determinants of the actually adopted change of agricultural products in the next decades, as well as reducing waste and losses. Changing consumer behavior through research-based innovations is an opportunity, but is still mainly at experimental intervention stages, such as with "nudging" and nutrition education in low- and high-income countries. Nutrition-sensitive agriculture aims at making nutritious foods available and accessible, thus focuses on an important cause of malnutrition (Webb and Kennedy 2014, Jaenicke and Virchow 2013, Balz et al. 2015).

The rapidly developing biotechnological tool of gene editing (CRIP-SPR-CAS9) is a tool to alter the characteristics of organisms on DNA level (Doudna and Charpentier 2014). The new technologies may be a game changer for improved nutritious quality of food as well as higher and more sustainable yields through improved plant characteristics such as health properties and resistance. They are promising with respect to complementing, but probably not replacing the potentials of transgenics, such as Vitamin A enriched rice, for nutritional improvement. Major advantages of gene editing technology are its preciseness, the cost-effectiveness and ease of application. Extensive research is ongoing in numerous areas of science. The opportunities and risks of CRIPR-CAS9 are intensely discussed in relation to human genome editing (Olson 2015). In crops several applications already emerge in plant innovations and food processing (Wolt et al. 2016; Chen and Gao 2014), and science-informed discussion about the opportunities and limitations of the technology in plants is needed as well. Regulation is an issue, just as with transgenics. Addressing ambiguities regarding the regulatory status of crop genome editing techniques is critical to their application for development of useful crop traits. It should focus on the nature of the novel phenotype developed, rather than the process of innovation development (Wolt et al. 2016).

3.3. Innovations to Improve Nutrition Quality and Address "Hidden Hunger"

Worldwide, an estimated 2 billion people are affected by hidden hunger, which refers to the lack of crucial micronutrients in the daily diet such as vitamin A, iron or iodine. Nutrition science has by now very strong evidence that the effects of a diet based on food with poor nutritional qualities are far-reaching. Reduced productivity, impairment of the cognitive and physical development of children or higher risks for women during childbirth – the consequences for human health, societies and economies are tremendous and deserve increased attention. Poor rural populations in low- and middle-income countries are typically affected most by micronutrient deficiencies. However, a growing focus is also on the problem of overweight and obesity since the (over-)consumption of highly processed foods with poor nutritional quality and lifestyles can be a cause of related malnutrition.

An important evolution in the past 10 years is the increase of the nutrient content of staple foods, such as wheat, maize, rice, beans, and sweet potatoes through plant breeding – an approach called biofortification (Bouis et al. 2013)the process of breeding nutrients into food crops, provides a comparatively cost-effective, sustainable, and long-term means of delivering more micronutrients. The biofortification strategy seeks to put the micronutrient-dense trait in those varieties that already have preferred agronomic and consumption traits, such as high yield and disease resistance. Marketed surpluses of these crops may make their way into retail outlets, reaching consumers first in rural and then urban areas. Progress to date in breeding and delivering biofortified crops is discussed. The nutrition evidence on bioavailability and efficacy is growing. Completed nutrition studies for each crop are briefly discussed. Human studies have included a variety of technologies, including stable isotope methods, which are among the most powerful to measure bioavailability and efficacy. Efficacy and effectiveness studies are available for orange-fleshed sweetpotato (OFSP. Biofortification is regarded as one major contributor to eliminating micronutrient deficiencies. Currently there are several complementary approaches to address hidden hunger, i.e. biofortification, fortification (industrial or household based with sprinkles), supplementation, and diet changing behavior (incl. making diverse foods accessible to households, for instance gardening or animal products). Each of them have their strength and limitations in terms of reach and costs, and need to be optimally scaled up in rural and urban settings, rather than pursued in isolation.

New scientific insights from micro-biome research may impact the scope for effective nutrition interventions in significant ways, as nutrient utilization is better understood (Kau et al. 2011). Better understanding interrelationships between diet, nutritional status, the immune system and microbial ecology in humans might open up new types of nutrition interventions. There is increasing evidence that the nutritional value of food is influenced in part by the structure and operations of a consumer's gut microbial community, and that food in turn shapes the microbiota and its vast collection of microbial genes (Kau et al. 2011).

3.4. Innovative Digital Technologies Serving Food and Nutrition

Biological innovations are increasingly unfolding their potentials in conjunction with digital innovations (GIS, precision agriculture, agriculture information on mobile phones and smartphones). The mobile phone has not only become the most important communication technology globally, but also offers numerous additional functions such as access to the internet, audio-visual recordings or financial transactions. Digital technology is a game changer for food and nutrition security. It potentially makes responding to hunger risks more effective. Farmers can be better informed about market opportunities and become strong users of innovations that fit their circumstances. On the consumer side, digital technologies can facilitate the provision and dissemination of information related to malnutrition. Furthermore, costs for nutrition program experts to reach their target groups, especially mothers and children in need, decrease. Much of these opportunities are yet to materialize, but the potentials are large. In particular, the advent of smartphones has opened up a whole new range of services to their users. At the same time, the nature of the internet is changing towards a network of diverse mobile devices which can collect, share, and analyze huge amounts of data and connect users around the globe, including in Africa, through social networks. Several services are already being offered to farmers with the help of mobile technologies (referred to as m-services, Baumüller 2016). Using information and communications technologies (ICT) such as global positioning and information systems, remote sensing or sensors to monitor climatic conditions, soils, or yield, farmers can detect temporal and spatial variability across their fields. They can then selectively treat their crop, either manually or through technologies that adjust their behavior in response to the gathered data. Much of the focus has been on variable rate application of inputs based on yield and soil monitoring (McBratney et al. 2005).

Many of the high-tech agricultural applications used in industrialized and a few developing countries are unlikely to be appropriated soon in development contexts given low levels of literacy, limited access to equipment, and small landholdings. However, the rapid spread of mobile phones and networks as well as advances in the Internet of Things (IoT) could lead to technology applications that are better adapted to the needs and capacities of small-scale producers. Farmers can use IoT services to assist with site-specific management of their fields, monitor the development of their crops, adjust their agricultural practices in response to the data, and track the sales of the produce. The information they gather is complemented by other information to help with planning, such as weather forecasts or price information for inputs and outputs. The inclusion of the next generation of millions of small farmers in ICT opportunities could also contribute to a reduced urban–rural divide.

3.5. Innovations for Small Farms in Transformation

The small farm economies are in structural change. Both Africa and Asia will be approaching a turning point from a farm size decrease to increase, and demand for labor-saving mechanization will rise. This structural change will impact the labor markets, thus spilling over into other economic sectors. Yet, this transition towards larger farms, especially in regions where small farms are dominant, will take a long time. Most of the worldwide 570 million farms are small farms. Such small farms are impacted by a rapidly changing context that affects the food situation – some positive, some risk increasing. Opportunities are increasingly seen outside agriculture labor markets; youth in many countries are leaving farming; the market value of land is rising because of agricultural price changes and the increasing influence of non-agricultural demand for land use, and land speculation.

Since most of the poor in the world reside on small farms (von Braun and Mirzabaev 2015) what happens on these small farms will be decisive to reduce poverty and hunger. By investing more in farms and by increasing efficiency of farming, a large portion of poverty and malnutrition could be reduced. Policy support should be aimed at promoting the dynamism within the family farm sector itself, but also enhancing the dynamic interactions and integration of the family farm sector into the rest of the economy. At the same time, land rights of small farmers must be protected by recording and by enforcing ownership against powerful international and domestic investors. Digitally supported ownership records can help with that, but rule of law is essential. Improved crop technology and improved animal production systems are essential for enhanced income earning capacities on small farms. Crop technologies that enhance healthy diets on millions of farms that partly consume their own food and in rural communities that depend on local markets remain of considerable importance for a long time to come.

Long before formal science institutions were established, farmers' innovations were changing and improving productivity of farming and food systems. It must not be forgotten that this type of bottom up initiatives is still an important force of innovation in which farmers are investing. Gupta (2016), who pioneered the "Honey Bee Network" making grass roots innovations visible and accessible through sharing among thousands of farmers in India, points out that "minds on the margin are not marginal minds". Wünscher and Tambo (2016) studied farmer innovations in Ghana and show that they can be a promising source of locally adapted, site-appropriate solutions which may be suitable for rapid and cost-effective dissemination. They point to the fact that a farmer's innovative capacity remains part of his capability, which can be made use of by changing incentive systems for innovation, e.g. in the form of contests. Farmers become creative, share their knowledge with institutions and other farmers, and engage in experimentation. This strengthens partnerships between farmers, extension officers, and scientists and increases the appreciation for farmer innovations among the involved stakeholders. Other new research points at the important role aspirations or lack thereof play for innovation and technology adoption in agriculture. Mekonnen and Gerber (2016) find in Ethiopia that farmers with less aspiration adopt innovative practices such as improved seeds and fertilizer less often. The upshot of this research is that innovation is endogenous to fundamental drivers, and not just a matter of transfer of knowledge and technology. Yet, transfer of innovation also plays important roles today. Relying just on bottom-up innovations would neglect opportunities offered by new research and applied scientific insights.

3.6. Protecting Nutrition in Volatile Markets and Conflicts

Actions for nutritional improvements must take the increasingly complex macro realities into account, incl. market failures and political conflicts which make interventions for nutrition more difficult. Extreme food price changes adversely affect nutrition of the poor and particularly child nutrition (Kalkuhl et al. 2016). Purchasing power is further constrained for acquiring a healthy diet under such circumstances. Several important factors were found to have been underestimated before the global food price crisis in 2007/08, such as the level of price instability, the exposure of producers and consumers, and potential social unrest. Yet, little protection against price shocks exists currently and the most vulnerable people remain with a limited capacity to quickly adjust to abrupt price changes. Thus, the need to improve resilience of agricultural markets remains as high as ever. Innovations to deal with volatility aim to promote the integration of different markets for improved risk-sharing among them. This does not only apply to an international context but also within countries. Furthermore, integrating markets also helps to cope with seasonality as distant markets have different seasonal patterns. Value chain analyses can help explain why in some cases low-income producers do not profit from market integration, e.g., because product standards exceed their capabilities. Thus, while promoting market integration, it is necessary to equip farmers with the necessary tools and training to enable them to participate and compete in markets. In addition, measures for prevention of excessive volatility include national and regional grain reserves and regulations that restrict excessive speculation in food commodity markets (Tadesse et al. 2014). The international community and many governments have yet to develop an effective risk management strategy to be well prepared for future crises (Kalkuhl et al. 2016). Improved early warning and information sharing is needed at regional and global level.

Of increasing relevance at an international scale is hunger in complex emergencies, i.e., when political conflicts, war, terrorism and environmental emergencies interact. More than 20 countries are affected and about 200 million people suffer from hunger and undernutrition in these countries. Syria, Yemen, Afghanistan, parts of Nigeria, South-Sudan and Burundi are examples. The human right to food is often violated in some of these settings, and hunger is implicitly a weapon when cities or localities are encircled, preventing food and other aid from entering. In these settings, hunger reduction depends on innovative cooperation between security policy, diplomacy, and development policy. Good examples for emergency relief would be innovations such as cash cards for local purchases facilitating positive leakages of essential goods across borders, or cell phone based money transfers that can be locally used to buy foods. Protecting nutrition as much as possible during crises and rebuilding thereafter must consider inequalities and discriminations that determine resilience or the lack thereof.

At first glance, agricultural technologies do not seem fit to play a positive role under circumstances of food price crises and complex emergencies with conflicts, however, in fact they do. Technologies that help reduce prices of healthy diets even under price volatility are important for the poor. Biofortified and fortified foods can be part of that. In some of the settings of complex emergencies, home-grown foods are of critical importance. Systems of dissemination of improved seeds for nutritious diets may be more resilient than public nutrition programs, and can be facilitated by informal distribution systems and civil society organizations, even under some complex emergencies.

4. Summing up Needs for Sustained Improvements and Implications

Efforts to sustainably eradicate hunger and malnutrition much depend on policies and programs that match the growing complexities of its causes and features. Technology pessimism and globalization skepticism is a factor in parts of wealthier world population segments. To the extent such attitudes adversely impact policies of developmental relevance, such as biological science based innovations and trade openness, they adversely affect food and nutrition security, and that would be unfair to the poor. Several concluding points shall be summarized here:

1. Undoubtedly, significant increases for availability of healthy food that is accessible and affordable by low-income people is needed in the coming five decades to address the current unmet and the future needs. Much of that increased demand needs to be met by production increases in emerging economies. The nutritional qualities of food need to be enhanced at the same time. This is where new agricultural technologies and improved distribution systems will have to play key roles.
2. Innovation for the sustainable agricultural development in the rural areas affected by malnutrition will remain a major part of solutions in order to facilitate income growth where it is most needed. Investing in food and agricultural research and development (R&D) is an important tool for broad based innovation, especially related to improved seeds. Nutrition science itself needs to progress and tap into the potentially promising insights from micro-biome research.
3. Bio-science advances help to ensure food security not only with respect to increased food supply, but can also enhance nutritional quality of the food produced. Fortification and biofortification of foods and nutrition sensitive agriculture should be scaled up for overcoming the micronutrient deficiencies soon. Regulations must not unduly constrain access to hunger reducing technological advances.
4. Many of the promising opportunities of the new digital technologies are yet to materialize, especially in contexts of developing countries, but the potentials for contributing to hunger reduction are large and need international engagement and support.
5. Since the end-hunger goal among the SDGs is not separable from related environmental sustainability goals, the environmental and climate change aspects of agricultural and land and water use change need strong attention. An essential component of resilient agriculture is an end of land and soil degradation.
6. Avoidance of nutritional burdens from crises (e.g. price shocks) require information and early warning systems, as well as better preparedness with improved trade and food reserves policies. The role of crop technology to contribute to resilience in complex emergencies should not be underestimated.
7. Innovation initiatives must follow principles of good governance. Strong alliances among the private and public sectors and as well nongovern-

mental organizations (NGOs) guided by rights-based approaches, are needed to end hunger and undernutrition. Access to hunger reducing technologies is part of such a rights-based agenda.

References

Alexandratos, N. and Bruinsma, J. (2012). World agriculture towards 2030/2050: the 2012 revision. ESA Working paper No. 12-03. Rome, FAO.

Balz, A.G., Heil, E.A. and Jordan, I. (2015). Nutrition-sensitive agriculture: new term or new concept? *Agriculture & Food Security*, 4(1). Available at: http://www.agricultureandfoodsecurity.com/content/4/1/6

Baumüller, H. (2016). Agricultural Service Delivery Through Mobile Phones: Local Innovation and Technological Opportunities in Kenya. In: F.W. Gatzweiler and J. von Braun (eds.): *Technological and Institutional Innovations for Marginalized Smallholders in Agricultural Development*. Springer. 143-159.

Bouis, H. E., J. Low, M. McEwan, and S. Tanumihardjo. 2013. *Biofortification: Evidence and Lessons Learned Linking Agriculture and Nutrition*. FAO and WHO, Rome. http://www.fao.org/fileadmin/user_upload/agn/pdf/Biofortification_paper.pdf

Chen, K. and Gao, C. (2014). Targeted genome modification technologies and their applications in crop improvements. *Plant Cell Rep* (2014) 33: 575. DOI:10.1007/s00299-013-1539-6

Doudna, J.A. and Charpentier, E. (2014). The new frontier of genome engineering with CRISPR-Cas9, *Science*, Vol. 346, Issue 6213, DOI: 10.1126/science.1258096

FAO (2011). *Global food losses and food waste – Extent, causes and prevention*, Rome.

Fogel, R.W. (1999). Catching Up with the Economy. *American Economic Review* 89(1), pp. 1-21. Available at: http://pubs.aeaweb.org/doi/abs/10.1257/aer.89.1.1

Gillespie, S., J. Hodge, S. Yosef, R. Pandya-Lorch ed. (2016) *Nourishing Millions. Stories of Change in Nutrition*. International Food Policy Research Institute. Washington DC.

Gillis, J. (2009). Norman Borlaug, Plant Scientist Who Fought Famine, Dies at 95. *New York Times*. Available at: http://www.nytimes.com/2009/09/14/business/energy-environment/14borlaug.html?pagewanted=all&_r=0

Gordon, R.J. (2016). *The Rise and Fall of American Growth: The U.S. Standard of Living since the Civil War*. Princeton University Press.

Gupta, A. (2016). “Grass roots Innovation”. Penguin Random House. India Gurgaon.

IFPRI, Welthungerhilfe and Concern International (2016). *Global Hunger Index*, Washington DC

Jaenicke, H. and Virchow, D. (2013). Entry points into a nutrition-sensitive agriculture. *Food Security*, 5(5), 679-692. Available at: http://link.springer.com/10.1007/s12571-013-0293-5

Kalkuhl, M., von Braun, J. and Torero, M. (eds) (2016). *Food Price Volatility and Its Implications for Food Security and Policy*. Cham: Springer International Publishing. http://link.springer.com/10.1007/978-3-319-28201-5.

Kau, A.L., Ahern, P.P., Griffin, N.W., Goodman, A.L. and Gordon, J.I. (2011). Human nutrition, the gut microbiome, and immune system: envisioning the future. *Nature*. 474(7351), pp. 327-336.

Lutz, W., Butz, W.P. and KC, S. (2014).

World Population & Human Capital in the Twenty-first Century: Executive Summary. IIASA, Laxenburg, Austria.

Maggio, A., van Criekinge, T. and Malingreau, J.P. (2015). Global Food Security 2030 – Assessing Trends in View of Guiding Future EU Policies. *JRC Science and Policy Reports*, Foresight Series. doi:10.2788/5992

McBratney, A., Whelan, B., Ancev, T. and Bouma, J. (2005). Future Directions of Precision Agriculture. *Precision Agriculture* 6(1), pp. 7-23. doi:10.1007/s11119-005-0681-8

Mekonnen, D.A and Gerber, N. (2016). The effect of aspirations on agricultural innovations in rural Ethiopia (ZEF Discussion Papers 214).

Milanovic, B. (2016). *Global Inequality – A New Approach for the Age of Globalization*. Harvard University Press.

Minten, B., T. Reardon, S. Das Gupta, Dinghuan Hu, K.A.S. Murshid (2016), Wastage in Food Value Chains in Developing Countries: Evidence from the Potato Sector in Asia, in Andrew Schmitz, P. Lynn Kennedy, Troy G. Schmitz (ed.) *Food Security in a Food Abundant World (Frontiers of Economics and Globalization, Volume 16)* Emerald Group Publishing Limited, pp. 225-238.

Olson, S. (2015). *International Summit on Human Gene Editing: A Global Discussion Committee on Science, Technology, and Law*; Policy and Global Affairs; National Academies of Sciences, Engineering, and Medicine. DOI: 10.17226/21913

Pinstrup-Andersen, P. (2013). Nutrition-sensitive Food Systems: From Rhetoric to Action. *Lancet* 382 (9890), pp. 375-6. http://linkinghub.elsevier.com/retrieve/pii/S0140673613610533

Schuster, M. and Torero, M. (2016). Toward a sustainable food system: Reducing food loss and waste. In *2016 Global Food Policy Report*. Chapter 3. pp. 22-31. Washington, D.C.: International Food Policy Research Institute (IFPRI). http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/130211

Shell (2013). New Lens Scenarios. A shift in perspective for a world in transition. http://www.shell.com/content/dam/royaldutchshell/documents/corporate/scenarios-newdoc.pdf

Tadesse, G., B. Algieri, M. Kahkuhl, and J. von Braun. 2014. Drivers and Triggers of International Food Price Spikes and Volatility. *Food Policy* 47, pp. 117-28. http://linkinghub.elsevier.com/retrieve/pii/S0306919213001188

van Dijk, M. and Meijerink, G.W. (2014). A review of global food security scenario and assessment studies: Results, gaps and research priorities. *Global Food Security*, Volume 3, Issues 3-4, pp. 227-238, http://dx.doi.org/10.1016/j.gfs.2014.09.004.

von Braun, J. and Gatzweiler, F. (Eds.) (2014). *Marginality – Addressing the Nexus of Poverty, Exclusion and Ecology.* Springer Netherlands. http://link.springer.com/book/10.1007%2F978-94-007-7061-4

von Braun, J. and Mirzabaev, A. (2015). Small Farms: Changing Structures and Roles in Economic Development. ZEF Discussion paper No. 204. Bonn.

Webb, P., and E. Kennedy. 2014. "Impacts of Agriculture on Nutrition: Nature of the Evidence and Research Gaps". *Food and Nutrition Bulletin* 35 (1): 126-32.

Wolt, J.D., Wang, K. and Yang, B. (2016). The Regulatory Status of Genome-edited Crops. *Plant Biotechnology*, Volume 14, Issue 2 2016 pp 510-518. DOI: 10.1111/pbi.12444

Wünscher, T. and Tambo, J.A. (2016). Identification and Acceleration of Farmer Innovativeness in Upper East Ghana. In F. Gatzweiler and J. von Braun (eds.) *Technological and Institutional Innovations for Marginalized Smallholders in Agricultural Development*, Springer, 163-180. Available at www.research4agrinnovation.org

Grain Yield Increase – a Role for Genetic Modification?

Peter Beyer

The challenge

There appears to be a general lack of awareness regarding the menace of continuing population growth and of the magnitude of the challenge of attaining food security in the forthcoming decades. The population equivalent of about one Germany (ca. 80 Mio) is currently being added to the planet annually, this unavoidably leading to a global human population of ca. 10 billion by 2050-70 (Gerland *et al.*, 2014). Competing demands for agricultural products for non-food purposes exacerbate the situation. There is increasing demand for cereal grain and soybean for use as feed in livestock production, especially in countries with rapid economic growth that is accompanied by dietary change like, for instance, in China (Hansen and Gale, 2015). Additionally, substantial land is devoted to extensive oil palm plantations to satisfy diverse industrial demands. Additional competition for starch and vegetable oil relates to biofuel production: bioethanol and biodiesel. These three key forces – population growth, animal feed production, chemical raw material/energy production – are driving demand for agricultural products to unprecedented levels: numerous studies have shown that feeding a more populated and more prosperous world will require an approximate doubling of agricultural production by 2050 (Tilman *et al.*, 2011).

Under the constraints of limited resources like arable land, water and fertilizers, the unpredictable conditions of global climate change and the notoriously low investment in agricultural R&D, achieving this doubling within only 30-40 years is one of THE challenges of the century. Further intensification of existing land use and further wild land clearing for agriculture appear as the most likely measures to be taken, thus dramatically exacerbating the environmental impact of agriculture with fatal consequences on terrestrial and marine ecosystems that are highly threatened already. The current global yield increases of the main crops are around 1% annually, resulting in predicted 2050 supply shortfalls of 67%, 42%, 38% and 55% of maize, rice, wheat and soybean, respectively (Ray *et al.*, 2013). In light of this, truly game-changing solutions are required. The unbiased consideration of all possible avenues is mandatory to achieve sustainable food security for the coming generations. Among these is modern plant science.

Possible contribution from plant science

Plant science has contributed to food security in the past. The Green Revolution of the 1960s, as the most shining example, consisted of a bundle of improvements in agricultural practices which incorporated novel semi-dwarf wheat and rice varieties as an essential component. Such plant types strongly increased the harvest index (the proportion of a crop that can be harvested). The discovery and its implementation were recognized with the award of the Nobel Peace Prize in 1970 to Dr. Norman Borlaug. The Green Revolution achieved an approximate yield duplication which was much needed at the time. It is a further duplication that is required today. The question simply is: can it be done again?

Modern Plant Science has dramatically increased scientific knowledge and tools over the past decades. Breeding techniques that are based on DNA markers, the identification of quantitative trait loci (QTLs) that control desired traits and their combination through marker-assisted backcrossing, the possibility of identifying genomic regions of interest by investigating entire genomes in genome-wide association studies (GWAS),the availability of fully sequenced genomes, the ease of introducing targeted mutations into selected genes through CRISPR-Cas9 etc. have altogether revolutionized plant breeding. But have all of these methodologies delivered any accepted general strategies related to yield increase?

Yield is a highly complex trait that incorporates a plethora of biological components. Yield depends on literally all of the numerous physiological processes involved in plant development from seed germination to flower setting and grain filling. Plant architecture is another important yield component. Moreover, interaction with the environment, such as the plant's capability of coping with different soils, making use of fertilizers, and withstanding abiotic stresses such as drought, heat and cold, all contribute to yield. The genetically encoded capability of being more or less susceptible to the attack of pathogenic viruses, bacteria fungi and insects (biotic stresses) add to the long list of yield determinants. Consequently, yield gain can be viewed in terms of loss avoidance to attain the crop plant's yield potential (Evans and Fischer 1993), defined as the yield that can be attained under optimal, non-limiting and controlled growth conditions. Given the many determinants, it is not surprising that the numerous publications on the genetics of crop yield, and the numerous QTLs determined across crop plants cannot provide any unifying and game-changing idea. Rather the whole issue is represented as being highly complex and there is general acceptance that – in essence – there is no single most important gene capable of controlling yield. Much more work would be required to decipher the underlying highly complex genetic and biochemical network. But this requires time that is not available.

It is however still possible to countenance single gene solutions for yield increase. As examples I call on the semi-dwarf wheat and rice varieties of the Green Revolution mentioned above. At the time, classical breeding was employed, where breeders did not need to know the genes (alleles) they were assembling. With today's knowledge, it can be stated that the spectacular yield improvements achieved were – in fact – based on single genes!

These so-called "green revolution genes" (see Hedden, 2003, for review) act on the pathway of the gibberellins, phytohormones controlling stem elongation. In rice, the responsible mutation affects the activity of GA 20-oxidase, an enzyme that catalyzes in the gibberellin biosynthetic pathway the conversion of a precursor molecule into the biologically active phytohormone. Semi-dwarf rice lines thus produce insufficient for normal stem elongation. In wheat, the gene affected is involved in the mode of action of gibberellin. Here, a signaling pathway leads from a gibberellin receptor to gibberellin-dependent gene expression and consequently, to stem elongation. In this pathway, the so-called Della proteins play a major role. Mutations in the wheat Della encoding genetic locus *Rht-1* cause partial insensitivity to gibberellin and reduced stem elongation. Thus, semi-dwarf wheat is partially "blind" for this phytohormone and does not respond sufficiently to the perfectly available phytohormone.

Transgenic single gene approaches to yield improvement

Transgenic solutions have already contributed substantially to yield improvement in terms of loss avoidance. They are essentially based on single gene types. Besides herbicide tolerant crops relying on bacterial herbicide-tolerant gene products that represent enzymes in important plant biochemical pathways or enzymes that inactivate the herbicide, there are the *Bacillus thuringiensis* insecticidal *cry* gene products that have revolutionized agriculture in many, but not all areas of the world (ISAAA 2016). As by 2016, the global area of biotech crops amounted to 185 million hectares with an approximately equal distribution between developing and industrial countries. These well-known biotech crops rank among the fastest adopted crop technologies in the world.

However, unlike loss avoidance to approximate the yield potential of a crop plant, other novel discoveries point to the possibility of increasing the maximum possible yield of crop plants (the potential yield), i.e. of increasing the physiological capacity to "produce more". Some selected very recent examples shall be given.

The transformation of maize with the gene termed *PLASTOCHRON1* encoding a cytochrome P450 enzyme was shown to very significantly increase biomass and grain yield in maize, evidently by prolonging the proliferative phase of cells. The improvements were found in an inbred as well as in a panel of hybrids in the field (Sun *et al.*, 2017).

By increasing the effectiveness of photosynthetic dark reactions through expression of a gene from *Brachypodium* encoding the Calvin-Benson cycle enzyme sedoheptulose-1,7-biphosphatase (SBPase), wheat grain yields could be increased by 30-40% in the greenhouse (Driever *et al.*, 2017).

A barley regulatory gene (SUSIBA2, a transcription factor), when transformed into rice under the control of a seed-specific promoter leads to the formation of longer panicles accommodating more filled grains together leading to a yield increase (expressed as g seed per plant) of +30% (Su *et al.*, 2015). The field-tested technology used confers a shift of carbon flux favoring the allocation of photosynthesis assimilates to above ground biomass, including seeds. Consequently, root exudates, the carbon source of methanogenic bacteria, are reduced. This leads to an up-to 10-fold reduction in the emission of the greenhouse gas methane. Rice paddies are the largest anthropogenic methane source with annual emissions of 25-100 million tons.

Fan *et al.* (2015) were able to increase rice yields by +40% in the field by expressing a gene coding for a variant of a nitrate transporter.

Own work (to be published) is based on the transformation of Golden Rice with an anti-apoptotic gene from Arabidopsis, *BAG4,* that is capable of attenuating a genetic program termed programmed cell death. We have found consistent yield increases over multiple generations in the greenhouse caused by larger and more grains on longer panicles, altogether giving a yield gain of +30%.

These examples are surprising: first by the diversity of the targeted biological processes, thus signaling a vast potential for yield improvement with single transgenes. Second, the magnitude of yield increases of 30-40% across all of these approaches is stunning, potentially a quantum leap, considering that a consistent increase of 3-5% per annum in the field would represent a more than welcome major achievement.

Discoveries have been made: what next?

These examples represent work done at public sector research institutions where scientists enjoy much room for curiosity- and hypothesis-driven work, with a high likeliness for serendipitous discoveries. In private sector research, the particular capacity is in turning discoveries into "useful" technologies. In the current regulatory environment, the costs for developing a transgenic crop plant from proof-of principle to the point where approval is granted and beyond, is in the tens of millions (Kalaitzandonakes *et al.*, 2007; Qaim, 2009), let alone the costs and capacities required for efficacy testing, marketing, and distribution. A typical public sector research grant is in the range of only a (very) few hundreds of thousands, maximally. Even conducting field trials or seeking IP protection – both necessary requirements to elicit the interest of industrial partners to cooperate – frequently represent unsurmountable hurdles. In this light, the published examples although potentially groundbreaking, of highest quality and holding great promise for the game-changing solutions required to achieve food security, run an equally great risk of remaining only interesting research results. The paths for developing GM crops, driven by political agendas, is cemented today and practicable for companies only. Can we really afford to reject from practical exploitation of such tax-payer funded discovery and knowledge? It is high time for a change. Opportunities can no longer be wasted in the light of the challenges ahead. Better funding and more capacity building in agricultural R&D can be a reasonable start.

"You better start swimming or you sink like a stone, for the times they are changing" (Bob Dylan, Nobel Prize in Literature Laureate, 2016.)

Citations

Driever SM, Simkin AJ, Alotaibi S, Fisk SJ, Madgwick PJ, Sparks CA, Jones HD, Lawson T, Parry MAJ, Raines CA (2017) Increased SBPase activity improves photosynthesis and grain yield in wheat grown in greenhouse conditions. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 26, 372, 20160384.

Evans LT, Fischer RA (1993) Yield potential: Its definition, measurement and significance. *Crop Sci.* 39, 1544-1561.

Fan X, Tang Z, Tan Y, Zhang Y, Luo B, Yang M, Lian X, Shen Q, Miller AJ, Xu G (2016) Overexpression of a pH-sensitive nitrate transporter in rice increases crop yield. *Proc. Natl. Acad. Sci. USA* 28, 7118-7123.

Gerland P, Raftery AE, Sevčíková H, Li N, Gu D, Spoorenberg T, Alkema L, Fosdick BK, Chunn J, Lalic N, Bay G, Buettner T, Heilig GK, Wilmoth J (2014) World population stabilization unlikely this century. *Science* 346, 234-237.

Hansen J., Gale F. (2014) China in the next decade: Rising meat demand and growing imports of feed. USDA-ERS Amber Waves.

Hedden P. (2003) The genes of the green revolution. *Trends Genet.* 19, 5-9.

ISAAA (2016) Global status of commercialized Biotech/GM Crops:2016. ISAAA Brief No. 52. ISAAA: Ithaca, NY. http://www.isaaa.org/resources/publications/briefs/52/default.asp

Kalaitzandonakes N, Alston JM, Bradford KJ (2007). Compliance costs for regulatory approval of new biotech crops. *Nat. Biotechnol.* 25, 509-511.

Qaim M (2009) The Economics of Genetically Modified Crops. *Annu. Rev. Resour. Economics* 1, 665-694.

Ray DK, Mueller ND, West PC, Foley, JA (2013) Yield trends are insufficient to double global crop production by 2050. *PlosOne* e66428.

Su J, Hu C, Yan X, Jin Y, Chen Z, Guan Q, Wang Y, Zhong D, Jansson C, Wang F, Schnürer A, Sun C (2015) Expression of barley SUSIBA2 transcription factor yields high-starch low-methane rice. *Nature* 523, 602-606.

Sun X, Cahill J, Van Hautegem T, Feys K, Whipple C, Novák O, Delbare S, Versteele C, Demuynck K, De Block J, Storme V, Claeys H, Van Lijsebettens M, Coussens G, Ljung K, De Vliegher A, Muszynski M, Inzé D, Nelissen H (2017) Altered expression of maize PLASTOCHRON1 enhances biomass and seed yield by extending cell division duration. *Nature Commun.* 8, 14752.

Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. *Proc. Natl, Acad. Sci. USA* 108, 20260-20264.

Reducing Mineral and Vitamin Deficiencies Through Biofortification: Progress Under HarvestPlus

Howarth Bouis

1. The Problem and Mineral and Vitamin Deficiencies

Mineral and vitamin deficiencies are a serious public health problem in developing countries. Vitamin A, iron, and zinc deficiencies affect the largest number of people throughout Africa, Asia, and Latin America. For example, in Sub-Saharan Africa the prevalence of vitamin A deficiency among preschool children ranges from 40% in west and central Africa to about 25% in southern Africa (WHO, 2009). Anemia affects about 40% of pregnant women and 62% of children in Africa, about half of which is estimated to be attributed to iron deficiency (WHO, 2015). Anemia levels have not improved over the last 20 years. Data on zinc deficiency is limited, but recent estimates suggest that 24% of Africans have inadequate zinc intakes, with pregnant women and young children at the highest risk of deficiency (Bailey *et al.*, 2015). Furthermore, half of children with vitamin and mineral deficiencies are suffering from multiple deficiencies (Micronutrient Initiative, 2009). Micronutrient deficiencies result in higher morbidity and mortality, reduced cognitive abilities and so lower educational attainment, and decreased work capacity and earning potential, with far-reaching consequences for future generations.

2. Interventions Implemented By the Nutrition Community To Combat Mineral and Vitamin Deficiencies

Several options exist to combat micronutrient deficiencies, including supplementation, fortification, and food-based approaches like dietary diversification. For children under two, breastfeeding, micronutrient powders, and nutrient-dense complementary foods can reduce the prevalence of micronutrient deficiencies.

Vitamin A supplementation is a targeted intervention that is considered as one of the most cost-effective interventions for improving child survival (Tan-Torres Edejer *et al.* 2005). Because it is associated with a reduced risk of all-cause mortality and a reduced incidence of diarrhea (Imdad *et al.* 2010), programs to supplement vitamin A are often integrated into national health policies.

Commercial food fortification, where trace amounts of micronutrients are added to staple foods or condiments during processing, allows consumers to consume recommended levels of micronutrients. Fortification has been particularly successful for iodized salt: 71% of the world's population has access to iodized salt and the number of iodine-deficient countries has decreased from 54 to 32 since 2003 (Andersson, Karumbunathan, and Zimmermann 2012). Common examples of fortification include adding B vitamins, iron, folic acid and/or zinc to wheat flour and adding vitamin A to cooking oil and sugar. Fortification is particularly effective for urban consumers, who purchase foods that have been commercially processed and fortified. Fortification is less suitable for reaching rural consumers who often do not have access to commercially produced foods. To reach those most in need, fortification must also be subsidized or mandatory, so the poor do not buy cheaper non-fortified alternatives.

An alternative to commercial fortification is home-based fortification systems, in which micronutrient powders or lipid-based nutrient supplements are added to food prepared in the home. Evidence of the acceptability and efficacy of home fortification is growing (Adu-Afarwuah *et al.* 2008; Dewey, Yang, and Boy 2009; De-Regil *et al.* 2013), but concerns remain that it is difficult to implement on a large scale and costly to monitor.

Special considerations are needed for young children. The transition period from breast milk or formula to solid foods is often accompanied by micronutrient deficiency in developing countries. Food-based approaches can include additions or changes to complementary feeding practices during this period, including a focus on nutrient-dense foods and the use of specially formulated micronutrient powders.

The drawbacks are that supplementation and fortification may not reach all intended beneficiaries (particularly in rural areas) due to required behaviour change and implementation constraints and costs. Both interventions involve yearly recurrent costs in every country; the cumulative annual costs of supplements and fortification can reach billions of dollars globally, especially if coverage rates improve over time (Bouis 2017). The need for supplements and fortification will decline as food systems provide the necessary intakes of vitamins and minerals through diverse diets at more affordable prices.

3. The Role of Agriculture To Reduce Mineral and Vitamin Deficiencies

Dietary diversity is strongly and positively associated with child nutrition status and growth, even when controlling for socioeconomic factors (Arimond and Ruel 2004). In the long term, dietary diversification is likely to ensure a balanced diet that includes the necessary micronutrients.

In general, however, dietary quality in developing countries is poor. Low incomes and high prices for non-staple foods such as vegetables, fruits, pulses, and animal products are the major constraints to improved dietary quality. While there is great national and regional variation in diets in developing countries, most are characterized by high staple food consumption, mainly cereal or root staple crops. Access to dietary sources of micronutrients, including animal-source protein, fruits, and vegetables, is a major challenge for many. These foods are often inaccessible because of high cost, limited local availability, and distribution challenges (Fanzo, 2012).

Non-staple foods are dense in vitamin and minerals, and bioavailability is particularly high for animal products; animal products are the most expensive source of dietary energy. The poor eat large amounts of food staples to acquire dietary energy – to keep from going hungry. They spend what little money is left for some, but far too little, dietary quality.

Traditionally, public research and development strategies have focused on increasing agricultural productivity in staple crops to reduce malnutrition. The Green Revolution prioritized the development of high-yielding varieties of major staple crops and intensifying production, increasing the total output of food staples and reducing staple food prices. From the 1970s to the mid-1990s, the price of staple foods (like rice and wheat) decreased relative to the price of micronutrient-rich non-staple foods (like vegetables and pulses). As a result, micronutrient rich foods became less affordable, particularly to the poor (Bouis 2000, Kennedy and Bouis 2003).

4. The Justification for Biofortification

Biofortification, the process of breeding nutrients into food crops, provides a comparatively cost-effective, sustainable, and long-term means of delivering more micronutrients. Biofortified staple foods cannot deliver as high a level of minerals and vitamins per day as supplements or industrially fortified foods, but they can help by increasing the daily adequacy of micronutrient intakes among individuals throughout the lifecycle (Bouis *et al.* 2011). Note that biofortification is not expected to treat micronutrient deficiencies or eliminate them in all population groups. No single intervention will solve the problem of micronutrient malnutrition, but biofortification complements existing interventions to sustainably provide micronutrients to the most vulnerable people in a comparatively inexpensive and cost-effective way (Bouis 1999; Nestel *et al.* 2006; Pfeiffer and McClafferty 2007; Qaim *et al.* 2007; Meenakshi *et al.* 2010).

Biofortification provides a feasible means of reaching malnourished populations who may have limited access to diverse diets, supplements, and commercially fortified foods. The biofortification strategy seeks to put the micronutrient-dense trait in those varieties that already have preferred agronomic and consumption traits, such as high yield. Marketed surpluses of these crops may make their way into retail outlets, reaching consumers in first rural and then urban areas, in contrast to complementary interventions, such as fortification and supplementation, that begin in urban centers.

Unlike the continual financial outlays required for supplementation and commercial fortification programs, a one-time investment in plant breeding can yield micronutrient-rich planting materials for farmers to grow for years to come. Varieties bred for one country can be evaluated for performance in, and adapted to, other geographies, multiplying the benefits of the initial investment. While recurrent expenditures are required for monitoring and maintaining these traits in crops, these are low compared to the cost of the initial development of the nutritionally improved crops and the establishment, institutionally speaking, of nutrient content as a legitimate breeding objective for the crop development pipelines of national and international research centers.

There are three common approaches to biofortification: agronomic, conventional, and transgenic. Agronomic biofortification provides temporary micronutrient increases through fertilizers. This approach is useful to increase micronutrients that can be directly absorbed by the plant, such as zinc, but less so for micronutrients that are synthesized in the plant and cannot be absorbed directly (Lyons and Cakmak 2012). Conventional plant breeding involves identifying and developing parent lines with high vitamin or mineral levels and crossing them over several generations to produce plants with the desired nutrient and agronomic traits. Transgenic plant breeding seeks to do the same in crops where the target nutrient does not naturally exist at the required levels.

With the above as background, for biofortification to be successful, three broad questions must be addressed:

- Can breeding increase the micronutrient density in food staples to target levels that will make a measurable and significant impact on nutritional status?
- When consumed under controlled conditions, will the extra nutrients bred into the food staples be absorbed and utilized at sufficient levels to improve micronutrient status?

– Will farmers grow the biofortified varieties and will consumers buy/eat them in sufficient quantities?

The following three sections summarize the evidence that all three of these broad issues can be addressed in the affirmative.

5. Crop Development

Plant breeding can increase nutrient levels in staple crops to target levels required for improving human nutrition, without compromising yield or farmer-preferred agronomic traits. The crop development process entails screening germsplasm for available genetic diversity, prebreeding parental genotypes, developing and testing micronutrient-dense germplasm, conducting genetic studies, and developing molecular markers to lower the costs and quicken the pace of breeding. After promising lines have been developed, they are tested in several locations across target environments to determine the genotype x environment interaction (GxE) – the influence of the growing environment on micronutrient expression. Robust regional testing enables reduced time-to-market for biofortified varieties.

Table 1. Breeding Targets (parts per million)

Provitamin A		**Sweet potato**	**Maize**	**Cassava**
	Baseline micronutrient content	2	0	0
	Additional content required	30	15	15
	Final target content	32	15	15
Iron		**Beans**	**Pearl Millet**	
	Baseline micronutrient content	50	47	
	Additional content required	44	30	
	Final target content	94	77	
Zinc		**Rice**	**Wheat**	
	Baseline micronutrient content	16	25	
	Additional content required	12	12	
	Final target content	28	37	

Source: HarvestPlus Breeding Program

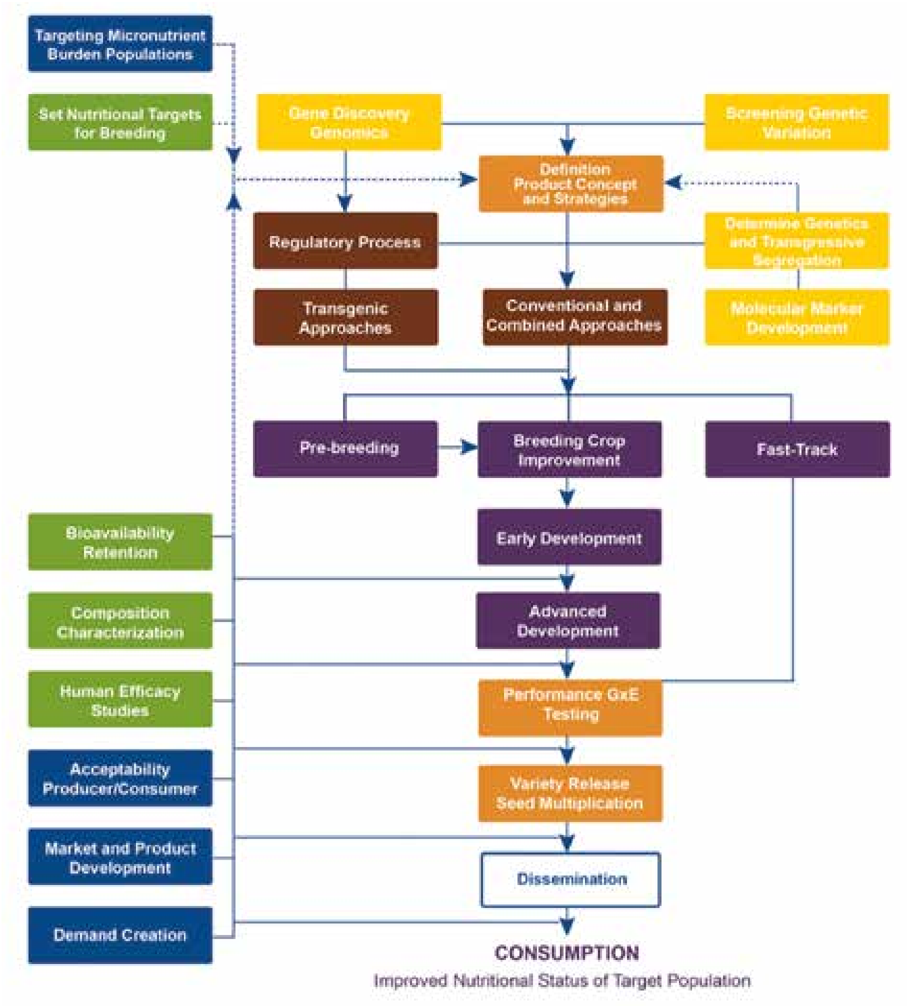


Figure 1. Crop development framework. Source: HarvestPlus.

Early in the conceptual development of biofortification, a working group of nutritionists, food technologists, and plant breeders established nutritional breeding targets by crop, based on food consumption patterns of target populations, estimated nutrient losses during storage and processing, and nutrient bioavailability (Hotz and McClafferty 2007). Breeding targets (Table 1) for biofortified crops were designed to meet the specific dietary needs and consumption patterns of women and children. Taking into account baseline micronutrient content in each crop, targets were set such that, for preschool children 4-6 years old and for non-pregnant, non-lactating women of reproductive age: the total amount of iron in iron beans and iron pearl millet will provide approximately 60% of the Estimated Average Requirement (EAR) (30% of the EAR for iron at baseline before breeding for high iron); zinc in zinc wheat and zinc rice will provide 60 to 80% of the EAR (40% of the EAR for zinc at baseline); and, provitamin A, the precursor of vitamin A, will provide 50% of the vitamin A EAR in the case of yellow cassava and orange maize, and up to 100% in the case of orange sweet potato (zero provitamin A at baseline). The breeding target is the sum of the baseline micronutrient content and additional micronutrient content required for each crop and micronutrient combination.[1]

Crop improvement activities for biofortification focus, first, on exploring the available genetic diversity for iron, zinc, and provitamin A carotenoids (yellow boxes in Figure 1). At the same time or during subsequent screening, agronomic and end-use features are characterized. The objectives when exploring the available genetic diversity are to identify: (1) parental genotypes that can be used in crosses, genetic studies, molecular-marker development, and parent-building, and (2) existing varieties, pre-varieties in the release pipeline, or finished germplasm products for "fast-tracking." Fast-tracking refers to releasing, commercializing, or introducing genotypes that combine the target micronutrient density with the required agronomic and end-use traits so they can be delivered without delay.

If variation is present in the strategic gene pool (only in unadapted sources), pre-breeding is necessary prior to using the trait in final product development; if variation is present in the adapted gene pool, the materials can be used directly to develop competitive varieties (purple boxes in Figure 1). Most breeding programs simultaneously conduct pre-breeding and product enhancement activities to develop germplasm combining high levels of one or more micronutrients.

The next breeding steps involve developing and testing micronutrient-dense germplasm, conducting genetic studies, and developing molecular markers to facilitate breeding. Genotype x environment interaction (GxE) – the influence of the growing environment on micronutrient expression – is then determined at experiment stations and in farmers' fields

[1] The breeding targets shown in Table 1 take into account per capita consumption, bioavailability, and retention during processing, storage, and cooking. All these parameters vary by crop. For details see Bouis and Saltzman, 2017b, chapter 1, especially Table 1.2.

in the target countries (orange boxes). The most promising varieties are selected for multi-locational testing over multiple seasons by national research partners, and then are submitted to national government agencies for testing for agronomic performance and release, a process which typically takes two years, sometimes more.

International Nurseries/Global Testing

Two strategies have been used to shorten time to market for biofortified crops: 1) identifying *adapted* varieties with significant micronutrient content for release and/or dissemination as "fast track" varieties, while varieties with target micronutrient content are still under development, and 2) deploying multi-location Regional Trials across a wide range of countries and sites to accelerate release processes by increasing available performance data of elite breeding materials. Regional Trials also include already-released biofortified varieties and generate data on their regional performance, in order to take advantage of regional variety release systems such as under SADC (Southern African Development Community). Such regional agreements harmonize seed regulations of member countries and allow any variety that is tested, approved, and released in one member country to be released simultaneously in other member countries with similar agro-ecologies.

Low-Cost, High Throughput Methods

Biofortification breeding required developing or adapting cost-effective and rapid high throughout analytical techniques for micronutrients, as thousands of samples need to be tested for mineral or vitamin content each season. These trait diagnostics include near-infrared spectroscopy (NIRS) and colorimetric methods for carotenoid analysis. For mineral analysis, X-ray fluorescence spectroscopy (XRF) emerged as the method of choice, as it requires minimal pre-analysis preparation and allows for non-destructive analysis (Paltridge *et al.* 2012a; Paltridge *et al.* 2012b).

Releases of Biofortified Crops

Cumulatively, more than 150 biofortified varieties of 10 crops have been released in 30 countries. Candidate biofortified varieties across 12 crops are being evaluated for release in an additional 25 countries. Figure 2 depicts where biofortified varieties have been tested and released to date. Biofortified crops have been released in countries indicated in dark purple, while crops are being tested in countries in light purple. This map includes countries where the International Potato Center (CIP) has worked to release the orange sweet potato. More detailed information about the varieties tested and released in each country is given in Bouis and Saltzman 2017b, Chapter 5.

Figure 2. Biofortified Crop Map (January 2017). Source: HarvestPlus[2]

6. Nutritional Bioavailability and Efficacy

To develop evidence of nutritional efficacy food scientists first measure retention of micronutrients in crops under typical processing, storage, and cooking practices to be sure that sufficient levels of vitamins and minerals will remain in foods that target populations typically eat (for summary results, see De Moura *et al.* 2015). Genotypic differences in retention and concentrations of compounds that inhibit or enhance micronutrient bioavailability are considered. Nutritionists also study the degree to which nutrients bred into crops are absorbed, first by using animal and other models, then by direct study in humans in controlled experiments. Absorption is a prerequisite to demonstrating that biofortified crops can improve micronutrient status, but the change in status with long-term intake of biofortified foods must be measured directly. Therefore, randomized controlled efficacy trials have been undertaken to demonstrate the impact of biofortified crops on micronutrient status and functional indicators of micronutrient status (i.e. visual adaptation to darkness for vitamin A crops, physical activity and cognition tests for iron crops, etc.). Highlights are discussed below. Further detail on retention is summarized in De Moura *et al.* (2014). Annex 1 provides a list of selected references on evidence for efficacy and effectiveness.

[2] To view country- or crop-specific information about varietal testing and release, see: http://harvestplus.org/sites/default/files/publications/HarvestPlus_BiofortifiedCropMap_2016.pdf

Iron Crops

Iron nutrition research has demonstrated the efficacy of biofortified iron bean and iron pearl millet in improving the nutritional status of target populations. In Rwanda, iron-depleted university women showed a significant increase in hemoglobin and total body iron after consuming biofortified beans for 4.5 months (Haas *et al.* 2016). The efficacy of iron pearl millet was evaluated in secondary school children from Maharashtra, India. A significant improvement in serum ferritin and total body iron was observed in iron-deficient adolescent boys and girls after consuming biofortified pearl millet flat bread twice daily for four months. The prevalence of iron deficiency was reduced significantly in the high-iron group. Those children who were iron deficient at baseline were significantly (64%) more likely to resolve their deficiency by six months (Finkelstein *et al.* 2015).

Vitamin A Crops

Vitamin A bioavailability studies found efficient conversions from provitamin A to retinol, the form of vitamin A used by the body. Efficacy studies demonstrated that increasing provitamin A intake through consuming vitamin A-biofortified crops results in increased circulating beta-carotene, and has a moderate effect on vitamin A status, as measured by serum retinol. Consumption of orange sweet potato (OSP) can result in a significant increase in vitamin A body stores across age groups (Haskell *et al.* 2004; Low *et al.* 2007; van Jaarsveld *et al.* 2005).

The primary evidence for the effectiveness of biofortification comes from OSP, assessed through a randomized controlled trial. The OSP intervention reached 24,000 households in Uganda and Mozambique from 2006-2009 with adoption rates of OSP greater than 60% above control communities (Hotz *et al.* 2012a, Hotz *et al.* 2012b). Introduction of OSP in rural Uganda resulted in increased vitamin A intakes among children and women, and improved vitamin A status among children – a decrease in the prevalence of low serum retinol by 9 percentage points. Women who got more vitamin A from OSP also had a lower likelihood of having marginal vitamin A deficiency (Hotz *et al.* 2012a). Recent research on the health benefits of biofortified OSP in Mozambique showed that biofortification can improve child health; consumption of biofortified orange sweet potato reduced the prevalence and duration of diarrhea in children under five (Jones & De Brauw 2015). For additional information on the development and delivery of OSP, see Low *et al.* (2017).

Biofortified provitamin A maize is an efficacious source of vitamin A when consumed as a staple crop. An efficacy study conducted in Zambia with 5 to 7-year-old children showed that, after three months of consumption, the total body stores of vitamin A in the children who were in the orange maize group increased significantly compared with those in the control group (Gannon *et al.* 2014). Consumption of orange maize has been demonstrated to improve total body vitamin A stores as effectively as supplementation (Gannon *et al.* 2014), and significantly improve visual function in marginally vitamin A deficient children (Palmer *et al.* 2016).

To date, only a small provitamin A cassava efficacy study has been completed in Eastern Kenya with 5 to 13-year-old children. This trial demonstrated small but significant improvements in vitamin A status, measured both by serum retinol and *beta*-carotene, in the yellow cassava versus the control group (Talsma *et al.* 2016). A larger-scale efficacy trial is underway in Nigeria.

Zinc Crops

Zinc studies have demonstrated that zinc in biofortified wheat is bioavailable (Rosado *et al.* 2009). Because plasma zinc concentration, the biomarker widely used to estimate zinc status, has limitations in measuring changes in dietary zinc, foundational research to identify and test more sensitive biomarkers is underway. These biomarkers will be tested in the zinc rice and wheat efficacy trial scheduled for 2017. A recent study showed that DNA strand breaks are a sensitive indicator of modest increases in zinc intake, such as the amount of additional zinc that might be delivered by a biofortified crop (King *et al.* 2016).

Future Areas of Investigation

Areas for further research include robust new trials that test the efficacy of biofortified crops for a wider range of age and gender groups, including infants, and over a longer time period (for example, prior to conception through infancy). Other research will test the efficacy of consuming several different biofortified crops, each providing different vitamins and/or minerals to the food basket. Nutritionists agree that biofortified crops can improve nutritional status in micronutrient-deficient populations, but additional research is needed, using other, more sensitive biochemical indicators, as well as functional indicators, to more fully understand the health impact of consuming biofortified foods.

7. Delivery Experiences in Target Counties

After biofortified varieties have been developed and released, they enter national farming and food systems. Research continues to develop evidence that farmers are willing to grow biofortified crops and that consumers are willing to eat them. An evidence base has been developed in eight target countries (Bangladesh, DR Congo, India, Nigeria, Pakistan, Rwanda, Uganda, and Zambia) by HarvestPlus and national partners. As of the end of 2016, it is estimated that more than 20 million people in developing countries are now growing and consuming biofortified crops (Bouis and Saltzman, 2017a).

Vegetatively Propagated Crops

Vegetatively propagated crops – those for which farmers plant stems, tubers or vines rather than seeds – typically have seed systems characterized by small, informal (rather than commercial) actors. Planting materials are perishable, expensive and bulky to transport over long distances, and must be replanted within several days of harvesting. The lack of commercial private sector participation creates both a challenge and an opportunity for producing planting materials of biofortified crops like orange sweet potato (distributed as vines) and provitamin A yellow cassava (distributed as stem cuttings). See Low *et al.* (2017) for additional evidence from OSP delivery.

Cassava in Nigeria and DR Congo

In parallel with strengthening the seed system through both community-based and commercial stem production, awareness of and demand for biofortified crops must be created simultaneously. In the case of provitamin A yellow cassava, extension to farmers was at the forefront of this effort. Initially, free bundles of stems were distributed to farmers, and accompanied by agronomic training and nutrition information. In the following season, farmers who received free stems were required to distribute an equal amount of free stems to two additional farmers, dramatically lowering delivery costs. This promotional strategy was effective in reaching vulnerable populations who typically do not have market access to improved varieties for planting. It also piqued interest and allowed farmers in a low-risk way to test a new product. Many of the farmers who received and planted free stems liked the yellow cassava and are now buying additional stems from commercial traders.

In 2015 it was estimated that about 75% of all biofortified harvested roots were consumed on farm, as many households were not yet producing excess from the stem packs they received for trial. Increased commercialization is expected going forward. As farmers began to produce yellow cassava in excess of their household food security needs, several activities were undertaken to increase awareness and demand from the food market for biofortified cassava. These efforts include consumer marketing via print, radio, and television media (even feature-length movies), and market development efforts by linking commercial food processing investors to supplies of yellow cassava roots.

Self-Pollinated Crops

Self-pollinated crops – those which produce seed true to their parent characteristics – can be replanted year after year. While farmers do need to periodically replace their seed to maintain its desirable agronomic traits, the possibility of self-production for seed typically limits private sector investment in producing seed for self-pollinated crops.[3] In many countries, the public sector instead multiplies and distributes self-pollinated seed, and further farmer-to-farmer dissemination is common. Self-pollinated biofortified crops include iron beans, delivered in Rwanda and Democratic Republic of Congo, zinc rice in Bangladesh, and zinc wheat in India and Pakistan.

Delivery has progressed most quickly in Rwanda, where initial public sector investments have now spurred private sector interest in meeting growing demand for iron bean seed. Significant delivery has also taken place in Bangladesh, where demand is driven by the zinc rice varieties that have attractive agronomic traits, including a short duration variety that allows for production of a third crop between the wet and dry season rice crops. Delivery of zinc wheat in India and Pakistan is just beginning. In India, zinc wheat is predominantly marketed by the private sector as truthfully labeled seed (TLS), and six private seed companies had incorporated zinc wheat into their product lines. In Pakistan, the first zinc wheat variety was released in 2016, and delivery through public and private sector partners is now underway.

Beans in Rwanda and DR Congo

In Rwanda, HarvestPlus worked closely with the Rwanda Agriculture Board (RAB) to facilitate production of bean seed through contracted farmers, cooperatives, and small seed companies. From 2011-2015, 80% of certified seed was procured through registered seed farmers under the supervision and certification of RAB, with the remainder being produced through contracts with local seed companies. To increase available seed for

[3] For crops with a low seed rate, like pearl millet, farmers are more likely to purchase seed annually. An open-pollinated variety of biofortified iron pearl millet, which combines the iron trait with 10% higher yield, has been successfully deployed through the private sector in India, where farmers generally purchase seed annually.

the 2015 planting season and beyond, established local and regional seed companies were engaged for seed multiplication, with RAB certifying the biofortified seed. A new seed class was proposed, "Declared Quality Seed" (DQS) or Certified II seed, first in Rwanda and then in DRC. DQS is produced from certified seed and is priced between certified seed and grain, bridging a price gap for farmers who are inclined to plant recycled grain rather than purchase certified seed.

Farmers initially accessed iron bean seed either in small quantities through direct marketing (via established agrodealers or in local markets) or in larger quantities through a payback system that also included cooperatives. By the end of 2014, marketing data showed that an increasing number of farmers were purchasing seed, a trend that is expected to continue. Farmer-to-farmer dissemination is also an important delivery channel; an impact assessment conducted in 2015 found that nearly half of farmers growing iron bean had received their planting material from a person in their social network (Asare-Marfo *et al.* 2016).

Because the iron trait is invisible and iron beans are not easily distinguished from conventional varieties, the primary approach has been to gain market share for biofortified beans due to their superior agronomic and consumption qualities. Over time, a high percentage of the total national supply of beans is expected to contain the biofortified trait, allowing access to additional iron for much of the population. A variety of delivery methods have been tested, including "swapping" biofortified seed for conventional seed, to ensure a high rate of farmer trial and adoption. Only five years after the first iron bean release, iron beans make up more than 10% of national bean production in Rwanda (Asare-Marfo *et al.* 2016).

Rice in Bangladesh

At the core of the Bangladesh strategy are rice varieties with attractive agronomic properties and a robust farmer demonstration program. One released zinc rice for the wet season (BRRI dhan 64) is a short duration variety (100 days as compared with 140 days), which allows production of a third crop of lentils or other food between wet and dry season rice crops. Other biofortified zinc rice varieties carry different farmer-preferred agronomic traits, like high height at maturity, which is beneficial for flooded areas in Southern Bangladesh. A robust demonstration program provides farmers a chance to observe these new varieties, as well as training on growing the biofortified rice and the health benefits of zinc.

Seed is produced by both the private and the public sector. A private seed association called SeedNet produces truthfully labeled seed alongside the foundation and certified seed produced by government entities. HarvestPlus initially both guarantees a market for a portion of the private sector production and subsidizes the price for any seed that the private sector markets directly to consumers. Free seed is distributed by NGO and government partners in small seed packs, and all free seed recipients agree to pass on the same amount of seed to three neighboring farmers in the subsequent season. As an increasing amount of zinc rice is available on the market, efforts to increase consumer and miller awareness have increased, including outreach via SMS and programs on local television and community radio channels.

Hybrid Crops

Hybrid crops – those for which seed must be replaced each year to maintain the same yield and agronomic traits – offer the most potential for private sector commercialization. While utilizing the private sector for delivery may lead to long-term sustainability, the speed of private sector uptake is dependent on their assessment of demand. Therefore, the activities of biofortification proponents must focus on targeted demand creation for both farmers and consumers.

Maize in Zambia

Because private seed companies dominate the hybrid maize seed market in Zambia, upon release, biofortified hybrid varieties were licensed to companies for commercialization of seed production and distribution. As biofortified maize is scaled up to reach more households in more provinces, the main challenge is to ensure extensive distribution through private networks to outlying areas. Because many rural households purchasing from agro-dealers cannot afford to buy large quantities of seed, private seed companies have begun to ensure that large quantities of smaller, affordable pack sizes will be available. The Zambia National Farmers Union and government extension services disseminate information to farmers about the availability of vitamin A maize seed in their local areas. The inclusion of orange maize seed in the Zambian government's Farmer Input Support Programme (FISP) has further facilitated access to orange maize, including for vulnerable households. FISP provides at least a 50% subsidy for maize seed and fertilizer to farmers considered economically disadvantaged. The quantity of orange maize seed distributed under FISP grew by 400% between the first and second year of inclusion in the program.

A central element of the delivery strategy is to create awareness and acceptance of orange maize through the use of social marketing campaigns and advertisements placed in public media, including TV, radio, newspapers, and popular music. Educational and awareness-creation activities stimulate consumer demand for orange maize products, while engagement with the private sector helps meet growing consumer demand.

To further stimulate cultivation of orange maize, creating markets for surplus production was essential, considering that 20 to 50% of rural households sell maize after satisfying their own food needs. HarvestPlus therefore links major grain buyers to farmers and offers grain samples to millers and food processors interested in incorporating orange maize in their product lines. The multi-lateral AgResults initiative also incentivizes millers to produce and market vitamin A maize products. Strong interest from farmers and food processors encourages increased private sector seed production.

Pearl Millet in India

Crop development and delivery in India is implemented through public and private sector partnerships. In crop development, ICRISAT supplies parental materials/breeder seeds for next stage seed multiplication. Partners now testing and developing their iron pearl millet varieties for seed sales include fifteen private seed companies, two public seed companies and five public organizations. ICRISAT develops high iron hybrid parental lines and to test hybrids with farmer-preferred traits, including of course high yields. This unique crop development arrangement supports and encourages companies to develop their own biofortified varieties for their target market segments. This approach is expected to more quickly increase the number and range of biofortified varieties available in the years to come.

Lessons Learned from Delivery

While delivery experiences vary widely by country and seed system, a few common themes have emerged from the delivery experience. First, multiplication of sufficient planting material is a crucial first step – without planting material to "prime the pump", farmers cannot be made aware of and will not be able to test biofortified crops. For example, there has been a focus on both strengthening capacity in the public and private sector to produce high quality seed and reducing risk, to ensure that quality planting material is available for farmers.

Second, demonstration trials have been key demand drivers at the farm level. Decentralized field demonstrations and the availability of small promotional seed packs have allowed interested farmers to view and try the new product without taking on a great deal of risk in cultivating a crop for which the market has not yet been tested. Third, nutrition messaging aimed at both men and women has also been key, and in general, involving women farmers has led to increasing demand for biofortified crops. While many biofortified crops are acceptable to farmers and consumers without further information about their nutrition traits, nutrition information helps ensure that the biofortified foods are integrated into child diets (Birol *et al.* 2015).

Finally, multi-stakeholder platforms are crucial to scaling up the early uptake and success of biofortified crops. In target countries, there has been rapid acceptance of biofortification by government entities, and national governments have proactively integrated it into their agriculture and nutrition policies. Integrating private and public sector actors and interests around shared goals reduces barriers to scaling.

8. Future Directions for Biofortification: Transgenic Approaches

Because conventional plant breeding does not face the same regulatory hurdles and is widely accepted, it is considered to be the fastest route to getting more nutritious crops into the hands of farmers and consumers. However, one of the very significant limitations thus far to conventional plant breeding is that the density of a *single* nutrient has been increased for each staple food crop – and that particular nutrient has been dictated by the variation of the nutrient density available in varieties stored in germplasm banks maintained by agricultural research centers.

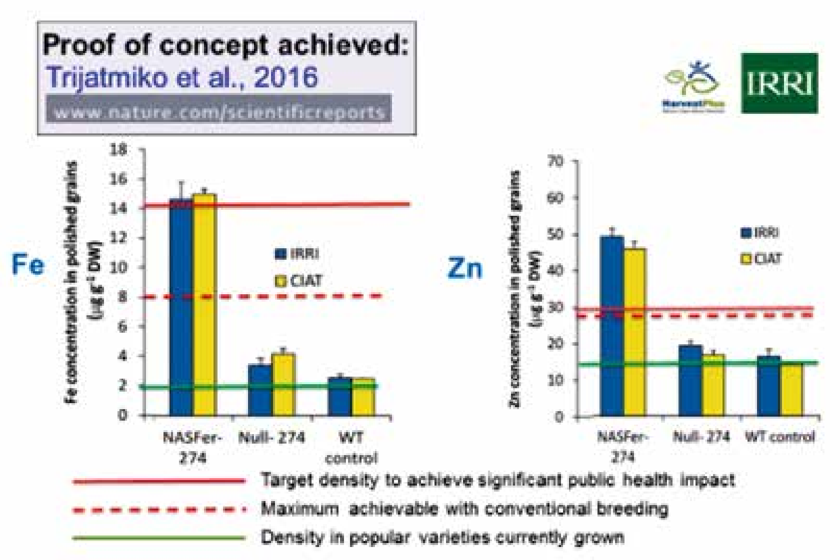


Figure 3. Transgenic Fe- and Zn-dense rice.

In crops where the target nutrient does not naturally exist at the required levels in the tens of thousands of varieties in germplasm banks, transgenic plant breeding is a promising approach to produce biofortified crops with the desired nutrient and agronomic traits – for single nutrients and for multiple nutrients as well.

For example, transgenic iron and zinc rice has been developed and tested in confined field trials that can provide +30% of the EAR for iron and +50% of the EAR for zinc in the same event (Trijatmiko *et al.* 2016). As can be seen in Figure 3, the event tested in two locations (IRRI in the Philippines and CIAT in Colombia) meets the iron target of (14 ppm Fe total or +12 ppm Fe) and exceeds the target for zinc by a very large margin (45 ppm Zn or +30 ppm Zn), in a high-yielding background.

Golden Rice, which contains beta-carotene, can provide more than 50% of the EAR for vitamin A. Despite being available as a prototype since early 2000, Golden Rice has not been introduced in any country, in large part due to highly risk-averse regulatory approval processes (Wesseler and Zilberman 2014). High iron-zinc and high provitamin A rice can be crossed to give transgenic rice with high levels of all three nutrients.

While these transgenic varieties have tremendous potential for nutritional impact, release to farmers depends on approval through very strict national biosafety and regulatory processes, which ignore scientific recommendations that transgenic crops are safe (European Commission 2010; Nicolia *et al.* 2014; National Academies of Sciences, Engineering and Medicine 2016; The Royal Society 2016).

9. Conclusion

Currently in Africa, maize is the most widely consumed food staple. Most maize is white. White varieties are often highly preferred, white varieties contain no provitamin A, yet vitamin A deficiency is a serious public health problem in Africa. High-yielding, orange varieties, high in provitamin A are now available to farmers consumers – at the same price (due to high yields) as white varieties. Consumers like the taste of orange varieties and other sensory attributes (e.g., aroma and texture) of vitamin A varieties, often in the absence of information about their nutritional benefits (Stevens and Winter-Nelson 2008, Pillay *et al.* 2011, Meenakshi *et al.* 2012). The value proposition to mothers is obvious: which do they grow/buy and consume – orange or white – to protect their families from vitamin A deficiencies?

Currently, the private sector completely dominates the production and marketing of white varieties. The task ahead is to motivate consumers to demand orange varieties, and for the private sector again to dominate the production and marketing of orange varieties. Twenty years from now, a granddaughter will ask her grandmother – did there used to be such a thing as white maize? And her grandmother will reply, yes, when she was a child maize was mostly white. After all, carrots used to be white.

The vision of HarvestPlus, the global leader in biofortification science and policy, is that one billion people will be benefitting from biofortified crops by 2030. If 20 to 25% of the primary staple food supplies are biofortified in a subset of the 60 countries where biofortified crops will have been released (see Figure 2), then one billion people will have been reached. If fully committed to, biofortification will be one of largest nutrition interventions ever implemented.

References

Adu-Afarwuah S., Lartey A., Brown K., Zlotkin S., Briend A., and K. Dewey (2008). Home Fortification of Complementary Foods with Micronutrient Supplements is Well Accepted and Has Positive Effects on Infant Iron Status in Ghana. *American Journal of Clinical Nutrition*; 87(4): 929-938.

Andersson M., Karumbunathan V., and M.B. Zimmermann (2012). Global Iodine Status in 2011 and Trends over the Past Decade. *Journal of Nutrition* 2012; 142: 744-750.

Arimond M. and M.T. Ruel (2004). Dietary Diversity is Associated with Child Nutritional Status: Evidence from 11 Demographic and Health Surveys. *Journal of Nutrition*; 134(10): 2579-2585.

Asare-Marfo D., Birol, E., Gonzalez, C. *et al.* (2013). Prioritizing countries for biofortification interventions using country-level data. HarvestPlus Working Paper No. 11. Washington, DC: International Food Policy Research Institute, HarvestPlus.

Asare-Marfo, D., Herrington, C., Birachi, E., *et al.* (2016). Assessing the adoption of high iron bean varieties and their impact on iron intakes and other livelihood outcomes in Rwanda. Main Survey Report. Washington, DC: International Food Policy Research Institute, HarvestPlus.

Babu, R., Palacios-Rojas, N., Gao, S., Yan, J. and K. Pixley. (2013). Validation of the effects of molecular marker polymorphisms in LcyE and CrtRB1 on provitamin A concentrations for 26 tropical maize populations. *Theor. Appl. Genet.* 126(2): 389-399.

Bailey, R., West K.P. Jr., and R.E. Black (2015). The Epidemiology of Global Micronutrient Deficiencies. *Annals of Nutrition & Metabolism* 2015; 66(suppl 2): 22-33.

Birol, E., Meenakshi J.V., Oparinde, A., Perez, S., and K. Tomlins. (2015). Developing country consumers' acceptance of biofortified foods: A synthesis. *Food Security* 7(3): 555-568.

Bouis, H.E. (1999). Economics of Enhanced Micronutrient Density in Food Staples. *Field Crops Res.*; 60:165-173.

Bouis, H.E. (2000). Improving Human Nutrition Through Agriculture. *Food and Nutrition Bulletin*; 21: 549-565.

Bouis, H.E. 2017. The Role of Agriculture and Biofortification in the Decade of Action on Nutrition (DOAN), SCN News.

Bouis H.E., Eozenou, P., and Rahman A. (2011). Food prices, household income, and resource allocation: Socioeconomic perspectives on their effects on dietary quality and nutritional status. *Food and Nutrition Bulletin* 32(1): S14-S23.

Bouis, H.E., Hotz, C., McClafferty, B., Meenakshi, J.V. and Pfeiffer, W.H. (2011). Biofortification: A new tool to reduce micronutrient malnutrition. *Food and Nutrition Bulletin* 32(Supplement 1): 31S-40S.

Bouis, H.E. and A. Saltzman. 2017a. Improving Nutrition Through Biofortification: A Review of Evidence from HarvestPlus, 2003 Through 2016. *Global Food Security*, Volume 12, March 2017, p. 58-67.

Bouis, H.E. and A. Saltzman, editors. 2017b. Special Issue on Biofortification. *African Journal of Food, Agriculture, Nutrition, and Development*. Volume 17, No. 2, April.

de Brauw, A., Eozenou, P., Gilligan, D.O., Hotz, C., Kumar, N., and Meenakshi, J.V. (2015). Biofortification, crop adoption, and health information: Impact pathways in Mozambique and Uganda. HarvestPlus Working Paper 21. Washington, DC: HarvestPlus.

De Moura, F., Miloff, A. and Boy, E. (2015). Retention of provitamin A carotenoids in staple crops targeted for biofortification in Africa: Cassava, maize, and sweet potato. *Critical Reviews in Food Science and Nutrition* 55(9): 1246-69.

De Moura, F., Palmer, A., Finkelstein, J. *et al.* (2014). Are biofortified staple food crops improving vitamin A and iron status in women and children? New evidence from efficacy trials. *Advances in Nutrition* 5: 568-570.

de Regil, L.M., Suchdev P., Vist G., Walleser S., and J.P. Pena-Rosas (2013). Home Fortification of Foods with Multiple Micronutrient Powders for Health and Nutrition in Children Under Two Years of Age. *Evidence-Based Child Health*; 8: 112-201.

Dewey K., Yang Z., and E. Boy (2009). Systematic Review and Meta-Analysis of Home Fortification of Complementary Foods. *Maternal and Child Nutrition* 2009; 5(4): 283-321.

European Commission, Directorate-General for Research and Innovation; Biotechnologies. 2010. A Decade of EU-Funded GMO Research (2001-2010). https://ec.europa.eu/research/biosociety/pdf/a_decade_of_eu-funded_gmo_research.pdf (Accessed 19 May 2016)

FAO, IFAD, and WFP. (2015). *The state of food insecurity in the world 2015.* Rome: FAO.

Fanzo J., Hunter D., Borelli, T., and F. Mattei (2012). *Diversifying Food and Diets: Using Agricultural Biodiversity to Improve Nutrition and Health*. New York, Routledge.

Finkelstein, J., Mehta, S., Udipi, S. *et al.* (2015). A randomized trial of iron-biofortified pearl millet in school children in India. *Journal of Nutrition*. DOI: 10.3945/jn.114.208009

Gannon, B., Kaliwile, C., Arscott, S. *et al.* (2014). Biofortified orange maize is as efficacious as a vitamin A supplement in Zambian children even in the presence of high liver reserves of vitamin A: a community-based, randomized placebo-controlled trial. *American Journal of Clinical Nutrition* 100(6): 1541-50.

Haas, J., S.V. Luna, M.G. Lung'aho, F. Ngabo, M. Wenger, L. Murray-Kolb, S. Beebe, J. Gahutu, and I. Egli. (2016). Consuming iron biofortified beans significantly improved iron status in Rwandan women after 18 weeks. *Journal of Nutrition,* forthcoming.

HarvestPlus. (2010). *Disseminating orange-fleshed sweet potato: Findings from a HarvestPlus project in Mozambique and Uganda*. Washington, DC: HarvestPlus.

Haskell, M.J., Jamil, K.M., Hassan, F., *et al.* (2004). Daily consumption of Indian spinach (Basella alba) or sweet potatoes has a positive effect on total-body vitamin A stores in Bangladeshi men. *American Journal of Clinical Nutrition* 80: 705-14.

Hoddinott, J., Rosegrant, M., and M. Torero. (2012). *Investments to reduce hunger and undernutrition*. Copenhagen Consensus Challenge Paper.

Hotz, C. and McClafferty. B. (2007). From harvest to health: Challenges for developing biofortified staple foods and determining their impact on micronutrient status. *Food and Nutrition Bulletin* 28(2): S-271-279.

Hotz, C., Loechl, C., de Brauw, A. *et al.* (2012a). A large-scale intervention to introduce orange sweet potato in rural Mozambique increases vitamin A intakes among children and women. *British Journal of Nutrition* 108: 163-176.

Hotz, C., Loechl, C., Lubowa, A. *et al.* (2012b). Introduction of B-carotene-rich orange sweet potato in rural Uganda results in increased vitamin A intakes among children and women and improved vitamin A status among children. *Journal of Nutrition* 142: 1871-1880.

Imdad A, Herzer K, Mayo-Wilson E, Yakoob MY, and ZA Bhutta (2010). Vitamin A Supplementation for Preventing Morbidity and Mortality in Children from 6 months to 5 Years of Age. *Cochrane Database of Systematic Reviews*; 12:CD008524.

Jones, K. and de Brauw, A. (2015). Using agriculture to improve child health: Promoting orange sweet potatoes reduces diarrhea. *World Development* 74: 15-24.

King, J., Brown, K., Gibson, R., Krebs, N., Lowe, N., Siekmann, J., and Raiten, D. (2016). Biomarkers of nutrition for development – Zinc review. *Journal of Nutrition*. doi: 10.3945/jn.115.220079

Lividini, K., and J. Fiedler. (2015). Assessing the promise of biofortification: A case study of high provitamin A maize in Zambia. *Food Policy* 54: 65-77.

Low J.W., Arimond, M., Osman, N. *et al.* (2007). A food-based approach introducing orange fleshed sweet potato increased vitamin A intake and serum retinol concentrations in young children in rural Mozambique. *Journal of Nutrition* 137: 1320-7.

Low, J.W., Mwanga, R., Andrade, M., Carey, E., and Ball, A. (2017). Tackling vitamin A deficiency with biofortified sweetpotato in sub-Saharan Africa. *Global Food Security,* Volume 12, March 2017, p. 49-57.

Lyons, G. and I. Cakmak (2012). Agronomic Biofortification of Food Crops with Micronutrients. In Bruulsema TW, Heffer P, Welch RM, Cakmak I and K Moran (Eds.) *Fertilizing Crops to Improve Human Health: A Scientific Review.* Paris, France: International Plant Nutrition Institute: 97-122.

Meenakshi J.V., Banerji A., Manyong V., Tomlins K., Mittal N., Hamukwala P. (2012). Using a discrete choice experiment to elicit the demand for a nutritious food: Willingness-to-pay for orange maize in rural Zambia. *Journal of Health Economics.* 31(1):62-71.

Meenakshi, J.V., Johnson, N., Manyong, V., De Groote, H., Javelosa, J., Yanggen, D., Naher, F., *et al.* (2010). How cost-effective is biofortification in combating micronutrient malnutrition? An ex-ante assessment. *World Development* 38(1): 64-75.

Micronutrient Initiative and UNICEF (2009) *Vitamin and Mineral Deficiency: A Global Progress Report*. Micronutrient Initiative, Ottawa.

National Academies of Sciences, Engineering, and Medicine. 2016. *Genetically Engineered Crops: Experiences and Prospects.* Washington, DC: The National Academies Press. doi: 10.17226/23395. http://www.nap.edu/23395

Nicolia, A., Manzo, A., Veronesi, F. and Rosellini, D., 2014. An overview of the last 10 years of genetically engineered crop safety research. *Critical Reviews in Biotechnology*, 34(1), 77-88.

Nestel, P., Bouis H.E., Meenakshi J.V., and W.H. Pfeiffer (2006). Biofortification of Staple Food Crops. *J. Nutr.*; 136:1064-1067.

Palmer, A.C., Healy, K., Barffour, M.A., Siamusantu, W., Chileshe, J., Schulze, K.J., West, K.P., Labrique, A.B. (2016). Provitamin A carotenoid-biofortified maize consumption increases pupillary responsiveness among Zambian children in a randomized controlled trial. *Journal of Nutrition*. doi: 10.3945/jn.116.239202

Paltridge, N.G., Milham, P.J., Ortiz-Monasterio, J.I., Velu, G., *et al.* (2012a). Energy-dispersive X-ray fluorescence spectrometry as a tool for zinc, iron and selenium analysis in whole grain wheat. *Plant Soil* 361: 261-269.

Paltridge, N.G., Palmer, L.J., Milham, P.J., Guild, G.E., *et al.* (2012b). Energy-dispersive X-ray fluorescence analysis of zinc and iron concentration in rice and pearl millet grain. *Plant Soil* 361: 251-260.

Pfeiffer, W.H. and B. McClafferty (2007). HarvestPlus: Breeding Crops for Better Nutrition. *Crop Sci.* 2007; 47:S88-S105.

Pillay, K., J. Derera, M. Siwela, & F.J. Veldman (2011). Consumer acceptance of yellow, provitamin A-biofortified maize in KwaZulu-Natal. *South African Journal of Clinical Nutrition* 24(4): 186-191.

Qaim, M., Stein A.J, and J.V. Meenakshi (2007). Economics of Biofortification. *Agric. Econ.*; 37:119-133.

Rosado, J., K.M. Hambidge, L. Miller, O. Garcia, J. Westcott, K. Gonzalez, J. Conde, C. Hotz, W. Pfeiffer, I. Ortiz-Monasterio, and N. Krebs. (2009). The quantity of zinc absorbed from wheat in adult women is enhanced by biofortification. *Journal of Nutrition* 139: 1920-1925.

Saltzman, A., Andersson, M.S., Asare-Marfo, D., Lividini, K., De Moura, F.F., Moursi, M., Oparinde, A., and V. Taleon. (2015). *Biofortification techniques to improve food security. Reference Module in Food Sciences.* Elsevier, pp. 1-9.

Saltzman, A., Birol, E., Bouis, H., *et al.* (2013). Biofortification: Progress toward a more nourishing future. *Global Food Security* 2 (1): 9-17.

Saltzman, Amy, Ekin Birol, Adewale Oparinde, Meike S. Andersson, Dorene Asare-Marfo, Michael T. Diressie, Carolina Gonzalez, Keith Lividini, Mourad Moursi, and Manfred Zeller. 2017. Availability, production, and consumption of crops biofortified by plant breeding: current evidence and future potential. Ann. N.Y. Acad. Sci. 1390; p. 104-114.

Stevens, R. & A. Winter-Nelson (2008). Consumer acceptance of provitamin A-biofortified maize in Maputo, Mozambique. *Food Policy* 33: 341-351.

Swamy, B.P.M., Rahman, M.A., Inabangan-Asilo, M.A., *et al.* (2016). Advances in breeding for high grain zinc in rice. *Rice* 9: 49. DOI 10.1186/s12284-016-0122-5

Talsma, E., I. Brouwer, H. Verhoef, G. Mbera, A. Mwangi, A. Demir, B. Maziya-Dixon, E. Boy, M. Zimmermann, and A. Melse-Boonstra. (2016). Biofortified yellow cassava and vitamin A status of Kenyan children: a randomized controlled trial. *American Journal of Clinical Nutrition* 103(1): 258-267.

Tan-Torres Edejer, T., Aikins M, Black R, Wolfson L,, Hutubessy R., and D. Evans (2005). Cost Effectiveness Analysis of Strategies for Child Health in Developing Countries. *British Medical Journal* 2005; 331: 1177.

The Royal Society. 2016. GM plants: Questions and answers. Issued: May 2016 DES3710. https://royalsociety.org/~/media/policy/projects/gm-plants/gm-plant-q-and-a.pdf

Trijatmiko, K.R., Duenas, C., Tsarkirpaloglou, N. *et al.* (2016). Biofortified indica rice attains iron and zinc nutrition dietary targets in the field. *Scientific Reports* 6: 19792.

van Jaarsveld, P.J., Faber, M., Tanumihardjo, S.A. *et al.* (2005). ß-carotene rich orange-fleshed sweet potato improves the vitamin A status of primary school children assessed with the modified-relative-dose-response test. *American Journal of Clinical Nutrition* 81: 1080-1087.

Wesseler, J. and D. Zilberman. (2014). The economic power of the Golden Rice opposition. *Environment and Development Economics* 19: 724-742.

World Bank (1993). *World development report.* Washington, D.C.

World Health Organization (WHO) (2009). Global Prevalence of Vitamin A Deficiency in Populations at Risk 1995-2005: WHO Global Database on Vitamin A Deficiency. WHO, Geneva.

World Health Organization (WHO) (2015). The Global Prevalence of Anaemia in 2011. WHO, Geneva.

Effects on Biodiversity

Peter H. Raven

In this paper, I shall deal with Genetically Modified (GM) crops in terms of their performance in the field and their effects on the environment generally. In order to do so properly, however, it is necessary first to provide a review of the context within which GM crops and domestic animals should appropriately be viewed. In general, misunderstandings, almost exclusively, have led to widespread controversies over the safety of the GM plants and animals in principle and of the safety for consumption of products derived from them by humans and domestic animals.

In general, the lateral transport of genes is frequent in nature and not some novel aberration that human beings have introduced into agricultural systems. For example, each of us has well over a hundred transgenes that were originally derived from some other kind of organism. These transgenes have been assimilated into our basic set of some 20,000 protein-coding genes, having proven either beneficial or neutral in the functioning of our bodies. No harmful effects have ever been attributed to any one of them, and they are transmitted like all of our other genes in a regular fashion from generation to generation.

In the course of evolution of organisms generally, the lateral transport of genes between unrelated kinds of organisms has been and remains frequent. Our Academy President, Professor Werner Arber, has been an active student of such genes, and has demonstrated numerous instances of their natural occurrence. In this context, a particularly interesting example concerns the genome of *Amborella*, a plant found only in the mossy forests of New Caledonia. *Amborella* displays a greater number of archaic features than any other kind of flowering plant, resembling the common ancestor of the phylum more closely than any other living genus. In its genome are located more than thirty transgenes, which have originated from at least four other distinct phyla. Such a finding certainly makes it clear that transgenes have played an important role in the evolution of *Amborella*. It seems likely that they will eventually be discovered as part of the genomes of most, if not all, other kinds of organisms, both prokaryotes and eukaryotes. The very long molecules of DNA that make up the genome of every kind of organism are neither more nor less than the organism's instructions for transcribing enzymes and other proteins through the intermediacy of

RNA. The molecules that are transcribed then direct all of the processes that lead to the particular features of individual organisms.

In general, then, altering the recipe embodied in an organism's DNA is therefore analogous to substituting a particular chord in a musical score, as a composer might do in the course of arriving at his or her final composition. If it "works", in either case, the gene or chord will be retained; and if it doesn't "work", the gene or chord will be eliminated sooner or later. In other words, if a new chord alters a musical score in a way that its composer finds pleasing, it will be retained; if not, it will be eliminated. In a similar fashion, if a new, introduced segment of DNA or gene alters the genome of the organism into which it is placed in a way that renders that organism better adapted to the environment in which that organism will attempt to survive, it will be retained, and it not, it will be eliminated. Such experimentation is clearly one of the ways in which the features of a musical score or a genome are improved, and the two processes are therefore somewhat analogous. In an organism, gene transfer may make possible more rapid adaptation to a particular habitat than would have been achieved by simple selection for particular existing alleles. In this way, gene transfer has become a relatively common feature of the process of adaption and therefore of biological evolution in general. The features of a particular organism are what lead to its improvement as a crop or its adaptation to a particular habitat, and not the particular route by which those features have evolved.

In considering the role of transgenes in domestic plants or animals, the massive genetic changes that our ancestors have wrought in them over up to 11,000 or more years of selection provide an appropriate context. Their earliest domesticated plants, which included flax, wheat, barley, lentils, vetch, and peas, have come over time to differ in varying degrees from their wild ancestors. These differences have come about as a result of thousands of generations of choosing seeds from the most productive and hardiest individual plants and sowing those particular seeds the following year. As a result, both of the original natural variation in such plants and animals and the occasional appearance of additional random mutations over the years, these plants became increasingly productive as sources of food – as did sheep, cattle, goats, chickens, and other domestic animals. Changes over the years have proceeded so far that there are no wild analogues of bread wheat, which is a hexaploid that does not occur in nature. The same is true of maize, which has come to differ so greatly from its wild progenitors that for decades, scientists experienced a very difficult time in determining which wild grasses were in fact its ancestors. And maize has been cultivated for "only" about 5,500 years!

Starting in England in about 1800, farmers have deliberately and with mathematical tools, selected in domestic plants and animals the characteristics that they valued most highly – sustainability under varying conditions, productivity, and so forth. That process of selection was refined greatly about a hundred years later, with the rediscovery of Mendel's laws of inheritance and their application to the process of selection. As breeders looked for even greater improvements than nature would easily allow, they began to apply strong chemicals and irradiation to the plants to break up and scramble their existing genomes into fragments that could be incorporated in various ways into other complete genomes. By doing so and growing the scrambled progeny that resulted, the breeders could sometimes produce individuals with features that were changed more fundamentally or in different directions than those that could easily be obtained by traditional breeding. Starting with such peculiar individuals, the breeders could stabilize unique new strains of crops by selecting for their new valued characteristics by further breeding and selection. Over the years, the results of these patently unnatural methods were fully accepted as a way of producing valuable new strains of crop plants, which were then adopted by farmers without reservation.

The possibilities for wide genetic transfer should not be surprising to us

The possibilities for wide genetic transfer should not be surprising to us. Human beings share more than 99% of their genomes with chimpanzees, bonobos, and gorillas and about two-thirds of their genomes with fruit flies, maize, and bananas, just to mention a few random kinds of organisms. Most of our genomes are inert (their base sequences are not transcribed), but direct comparisons of the functional genes in different kinds of organisms have also been carried out, and those sets of genes are strikingly similar also. For example, we have compared about 4,000 of our 20,000 genes, selected randomly, with those of tomatoes, finding that only 10 of the 4,000 genes examined proved different between ourselves and tomatoes.

Thus transgenes, like any other group of genes, are neither "good" nor "bad" as a class. Traditional breeding methods are capable of returning tomatoes or eggplants to their original poisonous nature in relatively few generations, but we don't choose to carry out that experiment in cultivated fields. In thinking about transgenes, or any other genes, the key point is *how do the characteristics they produce function in a living plant or animal – how do* *they modify its characteristics?* Among these undesirable characteristics would obviously be weediness. Considering that any new kind of plant or animal that is bred will be tested extensively before there is any thought of putting it on the market, we can see that there is clearly a degree of safety built into the system. If a particular crop already has weedy strains, as do sunflowers and sugar beets, then they might acquire immunity to pests or pesticides by cross breeding with the crop varieties; but such problems are both rare and obvious, so that steps are taken to avoid them. And in nature, if the wild strains become resistant to pests or parasites, or to chemicals, would that be a bad thing?

Are the products derived from GM plants and animals safe for consumption by humans and domestic animals grown to produce food for us? To help illuminate this subject, it can be pointed out that virtually all of the cheese, beer, and bread consumed anywhere in the world, as well as a large percentage of our medicines, including prominently all of our insulin, are produced using GM organisms. In the US and a number of other countries, our food is almost all produced from GM organisms too, and this has been true, with the proportion increasing, over a period of approximately 25 years. It is highly significant that during all of that time, not a single case of any problem or illness has been found among the hundreds of millions of people consuming these products every day or, for that matter, among the billions of farm animals consuming similar diets. The farmers who produced these products didn't make their choices to grow GM plants for no reason, or simply because someone told them to do so; they made these choices because their fields became more sustainable and productive when the GM strains were grown than otherwise. As a result, nearly all the maize and soybeans cultivation in the United States is now based on GM plants. For similar reasons, farmers in India have adopted GM cotton almost exclusively. When they are not legally prohibited for fanciful reasons, GM strains are very often more successful and productive that the others available in the same markets. Similar stories are developing throughout the world as people everywhere become familiar with the features of the GM plants that are increasingly available to them.

When we view these facts and relationships against a background of a hostile Europe making it difficult or impossible for starving people in Africa to be able to preserve their lives and improve their health by growing better strains of crops, when Europe has no problem feeding itself, then such denial seems to amount either to immorality or to ignorance. The problem is not only with food. Thus millions of people worldwide are denied access to adequate quantities of the micronutrients they need to preserve their lives and health, when there is no scientific evidence of harm from the sources for such micronutrients that are available if not legally prohibited. For example, over some 20 years, the use of Golden Rice, fortified with Vitamin A precursors, has been controversial for no scientific reason whatever. While this controversy has continued, millions of children have lost their sight and hundreds of thousands of have died because of their receiving insufficient amount of Vitamin A in their diets. In my opinion, such an outcome can only be termed disgusting, even obscene; it amounts to the rich making the poor abide by their arbitrary standards for no good reason except, perhaps, power. In the US itself, the organic food industry, currently US$50 billion, succeeded, against all rational considerations, in getting "GM" foods added to their criteria for "non-organic" produce, this designation functioning mainly as a selling point. When organizations that depend on public campaigns for their income continue to act in ways contrary to the known and established facts of a given situation, we may reasonably conclude that such organizations are acting primarily in their own financial self-interest. As such, their continued actions should be condemned and understood in the same light as we understand the tobacco industry, which has fought and continues to fight public understanding of the demonstrated harm that smoking does to the health of smokers.

What about the overall effects of growing GM plants on neighboring ecosystems? With some 40% or more of the Earth's surface already being cultivated or grazed to feed a rapidly growing population of 7.5 billion people, the effects of agriculture on biodiversity can only be described as catastrophic. The only way to limit further damage is to make agriculture as productive as possible in the areas that we already have under cultivation, so as not to destroy more of the natural landscape in the course of increasing our total yield. Obviously, fields that are intensively cultivated do not harbour a great deal of biodiversity, but agriculture that is not as productive as it can possible be destroys a large proportion of the existing biodiversity over what is intrinsically a much larger area. Should large-scale, "industrial" agriculture be practiced everywhere? Obviously not: small-scale agriculture works better in some regions, perennial plants are more sustainably productive than annual ones under some conditions, and agroforestry works best in others. Clearly, we need much research to determine what agricultural practices are best suited for the many different conditions in which we produce food. If we allow ourselves to remain confused about the factors that we need to take into account, as in assuming that GM plants or animals are harmful as a class, then we certainly will be limiting our ability to find the best answers for this problem. We certainly have no logical reason to assume that the particular genetic methods by which we derived the most productive plants should have any logical importance in making those decisions about agriculture.

In conclusion, transgenic technology is a modern development that fits into a very long succession of improvements in the methods used for plant breeding. Today, the importance of GM technology is being partly replaced by the more recently developed CRISPR technology, which offers even more precise methods and simpler methods of altering genes selectively. But the key point with which I want to leave you is that every allele of every gene is different; the characteristics that they produce in the particular organism are of ultimate significance, and not the methods by which they were produced. The is no disagreement about this point, or concerning the categorical safety of foods or other products derived from GM plants or animals, among all the academies of science or similar bodies anywhere in the world. The contrary articles that have appeared from time to time in the press, scientific or popular, have either been demonstrably incorrect or ultimately proved to be so. In fact, most such articles have been removed from the journals in which they have been published where there has been time to examine them in detail. Is it reasonable then, let alone ethical, to let hundreds of millions of people starve and others suffer the ravages of malnutrition because we have chosen an irrational course, and not taken the time to consider the facts in a deliberative, rational way? I think not, and hope that you will agree with me.

Sustained Soil Management. No Till Agriculture in Argentina

Mariano M. Bosch and Pablo A. Mercuri

1. Introduction

Brief description of Argentina and its agroindustrial sector

The purpose of this work is to demonstrate what the agricultural production system in Argentina consists of, what we do, how and why we do it.

Argentina, located in the southern tip of the American continent, has wide areas of soils suitable for agricultural production. Out of 279 million hectares, around 40 million are arable, that is to say 12.5% (Figure 1).

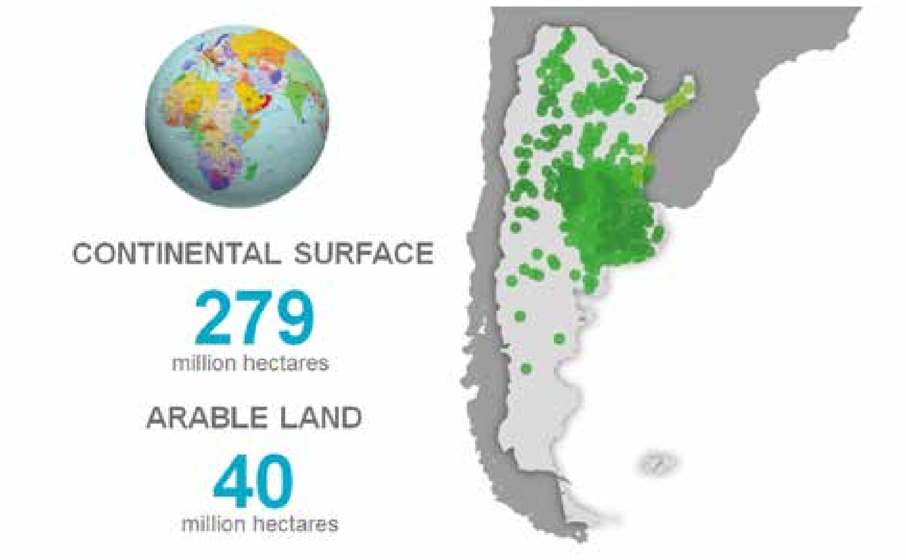


Figure 1. Argentina in the World.

The agro industrial sector contributes with 10% to 18% of the total GDP, which ranges from 550 to 600 billion US dollars. It is the main source of foreign exchange accounting for 60% of the total exports and 30% of workforce, direct and indirect employment (Figure 2).

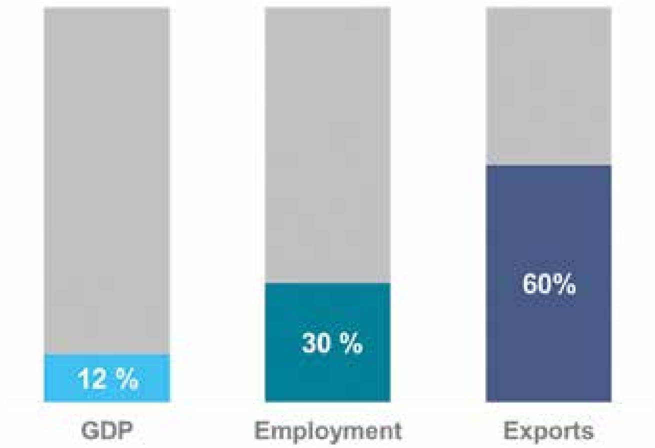


Figure 2. Argentina and the agroindustrial sector.

There have been significant changes in production systems through time. They changed from agricultural-livestock systems with rotation and conventional tillage to agricultural systems based on no till with crop rotation.

Livestock was moved to less agriculturally-suitable areas.

Over the past 20 to 25 years, the production of cereals and oilseeds has increased from 40 to 122 million tons.

This increase is due, firstly, to a higher cultivated surface (from 17.5 to 34 million hectares) as the result of the displacement of livestock and the expansion of the agricultural border. This expansion was mainly driven by No Till that allows agriculture in sub-humid or semiarid regions thanks to water economy, a factor we will analyze in detail later on, and also by the use of previously marginal lands because of their susceptibility to wind or water erosion.

Secondly, it is due to a higher production per hectare: genetic breeding and good crop management which allowed to go from an average of 2.4 tons per hectare to 3.7 tons per Ha for the main cereals and oilseeds (Figure 3).

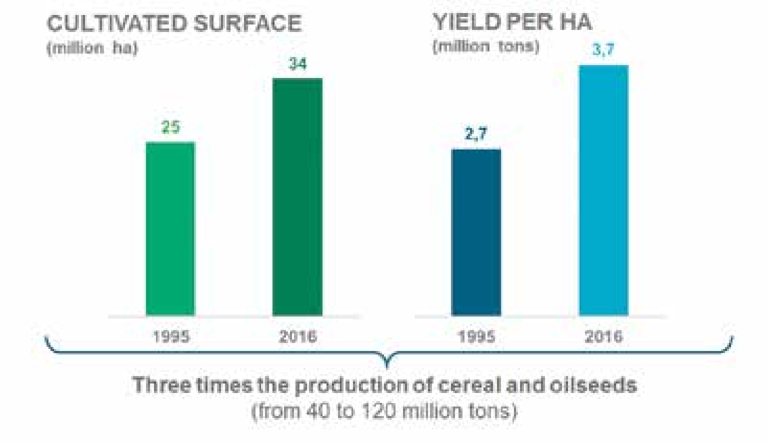


Figure 3. Evolution of the production system in Argentina.

2. What is No Till and how it spread in Argentina

The conventional tillage system is based on the old paradigm of agriculture with a till inverting and crumbling the soil, baring it for seeding. On the other hand, in no till the soil is practically not disturbed and upon harvest, remnants of threshing are spread on the soil. This together with the stubble generate a protecting cover against the impact of rain, wind and sun (Figures 4 and 5).

It began as a conservationist practice in the mid-70s and, in the 90s, it was massively adopted when, due to the knowledge and initiative of producers and technicians, they started to use GMO crops, resistant to herbicides and insects, in no till and good agricultural practices. Producers thus benefit from greater profitability and agriculture recovers competitiveness.

The spread of this system in Argentina was accompanied by the development of machinery which solved the problem of seeding on stubble coverage. Argentine producers joined and encouraged industry and today there are more than fifty Argentine factories manufacturing no till seeders and sprayers (Pognante et al. 2011; Bragachinni et al. 2015).

Figure 4. Conventional tillage vs. no-till.

Figure 5. Difference between a corn field under conventional tillage and a corn field under no-till production system.

3. Benefits of no till

The benefits for the soil, water use, productivity and sustainability are the following:

I. Control of wind and water erosion: soil cover, which is kept throughout the year, decreases direct wind action and improves infiltration avoiding soil damage and wind erosion. Better infiltration also reduces water runoff and soil loss to low areas and water courses. Areas with steep slopes must be accompanied with other conservation practices like terracing and contour lines (Colazo and Buschiazzo 2010; Pognante et al. 2011; Gil 2012).

Figure 6. Conventional Tillage: wind and water soil erosion.

II. Water use efficiency: lower losses by direct evaporation of the soil added to better infiltration determine greater availability of water for crops especially in the first 30 cm of the soil profile. This is beneficial in agricultural production of sub-humid and semi-arid areas, where in long periods of water deficit, greater crop resistance can be observed. This is contrary to what happens in conventional tillage where there is a higher superficial drying and, in less time, water is no longer available. In several trails, between 25 to 50% higher efficiency of water storage in soil was measured, compared to the conventional system (Figure 7). This implies a better efficiency of water use in grain production and also a production system more adapted to current and future climate variability (Derpsch 2001; Díaz Zorita et al. 2002; Gil 2012).

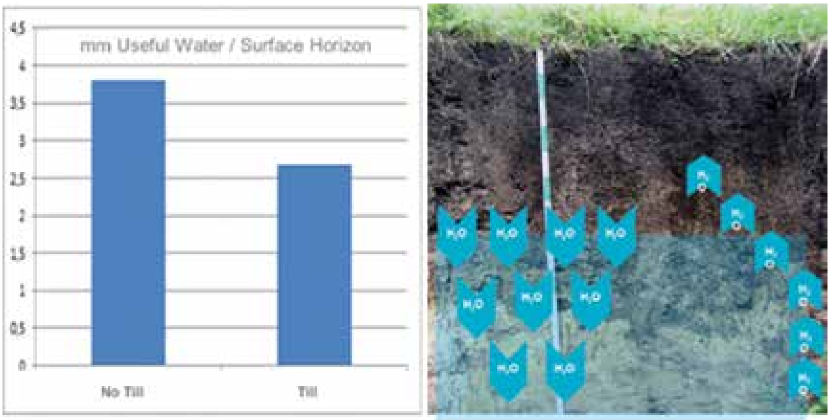


Figure 7. Conventional Tillage: wind and water soil erosion (Adapted from Alvarez et al. 2009).

III. Increase of organic matter and improvement in soil structure: The level of organic matter in soil is considered as one of the main indicators of its quality. In different types of soil, higher organic matter content has been found, after 10-15 years of rotation, in the first centimetres of soil under no till than in conventional tillage (Figure 8), (Blair et al. 2006).

Improvement in the physical structure of the soil is shown in greater porosity and stability of soil aggregates and better root development (Studdert y Echeverria 2002; *Díaz-Zorita et al*. 2004).

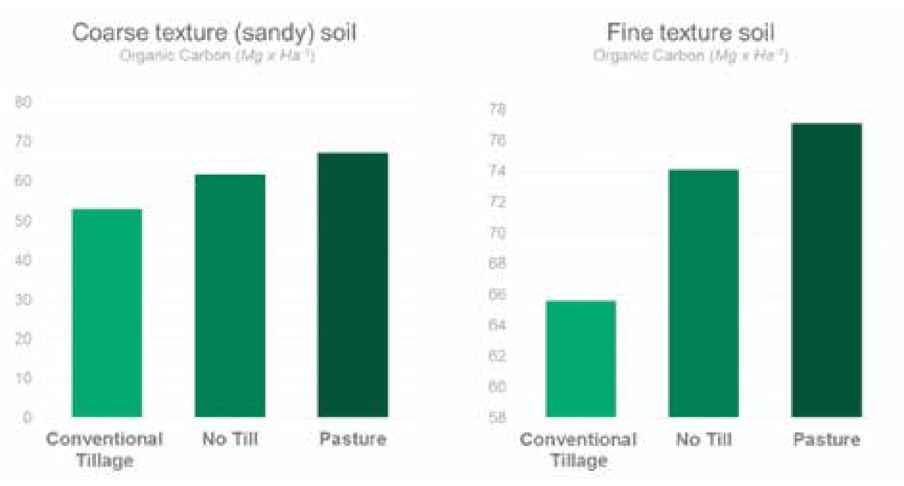


Figure 8. Increase carbon and organic matter in soil.

IV. Greenhouse gases: From the point of view of the carbon cycle, in no till, carbon dioxide is transferred from the atmosphere to the soil through biomass, becoming an agricultural practice to mitigate the greenhouse effect.

Besides increasing carbon in soil, reduction of emissions has also been proven. Research carried out by the Department of Agronomy at Purdue University in the United States proved that emissions in no till were 57% lower than in conventional tillage (Omonode et al., 2011).

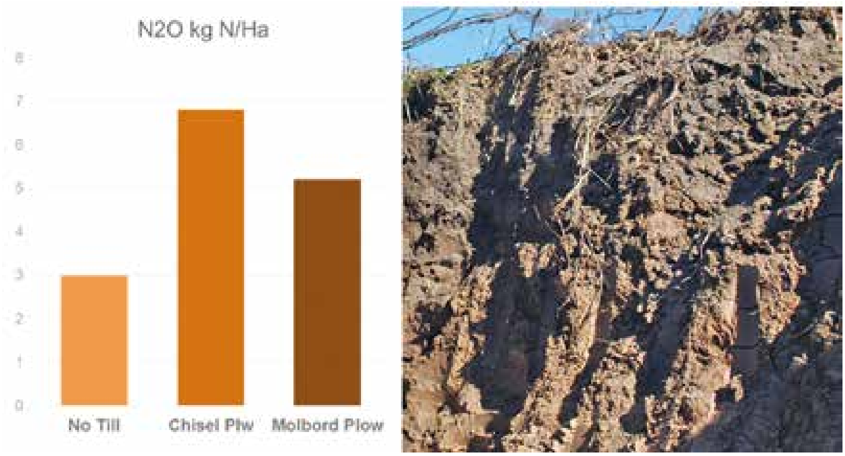


Figure 9. Reduction in Greenhouse Gases Emisions.

V. Greater biological diversity: stability in temperature, soil moisture and structure create ideal conditions for microbial and fungal activity, nematodes and soil worms, and arthropods in general (Paul 2007; Gil 1999).

VI. Less energy: around 70% less fuel is consumed, and up to 50% of tractor power is saved (lightweight and fewer trips) (Gil, 2012).

VII. Time opportunity: solid soil and more surface moisture allow sowing, spraying and harvesting in longer windows of time. However, lower soil temperature sometimes conspires against the advancement of sowing dates.

VIII. Yield stability: important attribute for sustainability which has been proven in different edaphic environments, different crops and over many years. Actually, it is the result of greater water use efficiency and improvement in Organic Matter and soil structure.

Place	Crop	Years	Number of Fields	No Tillage (kg/Ha)	Cv	Conventional Tillage (Kg/Ha)	cv	Author
Argentina (Tornquist)	Wheat,Corn,-Sunflower	26	2	2370	0,54	1906	0,61	Galantini, Keine, 2013
USA (Virginia)	Corn	4	1	7655	-	6101	-	Moeschler et al., 1972
Argentina (NW Buenos Aires)	Corn	7	200	6280	-	6000	-	Díaz Zorita et al. 2002
Argentina (NW Buenos Aires)	Soybean	7	200	1900	-	1950	-	Díaz Zorita et al. 2002
Argentina (Barrow)	Sunflower	3	1	1623	0,21	1890	0,25	Forjan et al., 2003
USA (Kellog – Michigan)	Wheat	3	5	3500	0,17	3650	0,16	Smith et al.,2007
USA (Illinois)	Corn	3	1	10796	0,2	11361	0,23	Nafziger, 2011

Table 1. Stability of yields.

4. Requirements for the proper functioning of this production system

Since no till is a technique within a Production system and Sustainable management, almost none of abovementioned benefits are obtained, nor can sustainability be achieved in the long term, if the principles of *Good Agricultural Practices* are not met.

- Crop rotation (grass should be included)
- Full and continuous soil cover (sometimes achieved by double-cropping or even cover crops)
- Replacement and balance of nutrients
- Systems approach to pest and weed management.

5. Emerging problems in the production system of Argentina

In parallel to the benefits listed before, there are some emerging problems to be solved. Among these are the following:

- The occurrence of resistant weeds
- Subsurface compaction due to the passing of machinery
- Excessive use of herbicides and insecticides
- Contamination, mainly in peri-urban areas
- Natural tendency of producers to abandon rotation and sow a more profitable crop.

Figure 10. Soybean field managed under no-till.

6. Constraints in the use of no till

A brief list of reasons for the delay in adopting and anticipating the inconveniences that may exist at the beginning of this path:

- Unawareness and change resistance
- Lack of appropriate machinery and skilled operators
- Adverse economic conditions that do not allow for adequate crop rotation (e.g. a price relationship that discourages or overstimulates certain crops)
- Prejudices and myths about biotechnology and the use of GMOs
- Inherited situations due to poor soil management (e.g. compaction) which must be corrected before starting with No Till.

7. Development, innovation and social sustainability

It is necessary to promote development instruments such as integration and associativism among producers' communities, industrialization of primary production in origin, add value, transform production, generate genuine jobs. This will allow a wide range of investment possibilities in different regions of the country, and above all the settling down and work of men and women in their region.

It is also necessary to continuously adopt technologies such as:

- Precision agriculture
- New germplasm and GMO crops
- New criteria in fertilization

- Innovation in machinery and new management practices
- Include a greater use of plant eco-physiology and ecology concepts, etc.

8. Regulatory framework and public-private interaction

In 1991 Argentina created the National Advisory Commission on Agricultural Biotechnology – CONABIA – which regulates the activities related to genetically modified organisms (GMOs) for agricultural use. This commission generated a regulatory framework which was been recognized internationally by FAO in 2014 as a reference centre for biosafety and GMOs worldwide. Full use of biotechnology in an extensive production framework has mainly occurred with soybean, corn and cotton events (CONABIA, 2016).

Commitment and institutional support are key to changing the paradigms and adopting new technologies. Argentina has a public institution which will be 60 years old in the next days, INTA, a research and extension institute which carries out research and promotes the use of technologies for the whole range of Argentine producers. Institution which today I represent as vice-president.

Also private non-profit institutions, made up of agricultural producers who have been able to promote the entrepreneurial spirit and their integral views, and are active participants in these processes of change and adoption of new technologies. Among them we can mention the Argentine Association of Regional Consortiums for Agricultural Experimentation (AACREA) and the Argentine Association for Direct Sowing Producers (AAPRESID).

9. Conclusions

Historically, agriculture is equivalent to tillage, and soil plowing. Moreover, currently, around 90% of the total world surface under agricultural production is still under this system. No till is a practice with long-term benefits which could be adopted in other parts of the world.

The synergy of the no till system with biotechnology and good management practices allows significant progress in large-scale food production, contributing to maintain the inter-annual stability of agricultural food production, consistent with sustainable development goals and the preservation of natural resources.

In the future, mankind and nature face the challenge of increasing food production by optimizing the use of resources, preserving soil and water, and offering at the same time a mitigation alternative and adaptation to climate change. In order to achieve the objectives of producing required food and reducing environmental impact, the future manifestation of our creative and innovative capacity must be to adapt, transfer and develop technologies that result in greater production, better use of resources and inputs, and lower environmental impact (Andrade, 2016).

This is why we consider that perfecting and disseminating this production system is not only a professional duty but also an important moral responsibility.

Acknowledgements

Our most sincere gratitude to the Pontifical Academy of Sciences, its Chancellor Monsignor Marcelo Sánchez Sorondo, the president of the Academy Dr. Werner Arber and Dr. Ingo Potrikus, for inviting us to contribute with our approach on agricultural production systems. To the many scientists and extensionists of INTA who contributed with their results and comments. Special thanks to Rodolfo Gil for his insights and contributions.

Bibliography

Alvarez, C.R., Taboada M.A., Gutierrez Boem F.H., Bono A., Fernández P.L. y Prystupa, P. 2009. Topsoil properties as affected by tillage systems in the Rolling Pampa region of Argentina. *Soil Science Society of America Journal*, 73: 1242-1250.

Andrade F. 2016. Los desafíos de la agricultura, 1ed. IPNI. 136 pages.

Blair N., Faulkner R.D., Till A.R., Poulton P.R. 2006. Long-term management impacts on soil C, N and physical fertility: Part I: Broadbalk experiment. *Soil Till. Res.*, 91 (2006), pp. 30-38.

Bragachini, M., Vélez, J.P., Casini, C., Sánchez, F., 2015. *No-till planting. A contribution to productivity and environmental sustainability*. Actualización Técnica Nº 89. INTA Manfredi. Ediciones INTA.

Colazo J.C., Buschiazzo D.E. 2010. Soil dry aggregate stability and wind erodible fraction in a semiarid environment of Argentina. *Geoderma* 159: 228-236.

CONABIA. 2016. http://www.agroindustria.gob.ar/sitio/areas/biotecnologia/conabia/

DeLaune, P.B., and J.W. Sij, 2012. Impact of tillage on runoff in long trrm no-till wheat system. *Soil and Tillage Research*. 124: 32-35.

Derpsch, R. 2001. Frontiers in Conservation Tillage and Advances in Conservation Practice. p. 248-254. In: D.E. Stott, R.H. Mohtar and G.C. Steinhardt (eds). 2001, *Sustaining the Global Farm*. Selected papers from the 10th International Soil Conservation Organization Meeting held May 24-29, 1999 at Purdue University and the USDA-ARS National Soil Erosion Research Laboratory.

Díaz Zorita, M., G. Duarte, and J. Grove. 2002. A review of no-till systems and soil management for sustainable crop production in the subhumid and semiarid Pampas of Argentina. *Soil Till. Res.* 65:1-18.

Díaz-Zorita, M., J.H. Grove, L. Murdock, J. Herbek y E. Perfect. 2004. Soil structural disturbance effects on crop yields and soil properties in a no-till production system. *Agron. J.* 96: 1651-1659.

Díaz-Zorita, M., M. Barraco y C. Alvarez. 2004. Efectos de doce años de labranzas en un Hapludol del noroeste de Buenos Aires, Argentina. *Ciencia del Suelo* 22: 11-18.

Forján, H.J.; Bergh, R; Zamora, M.; Seghezzo, M. y Molfese, E. 2003. Evaluación de girasol en siembra directa y labranza convencional sobre distinta historia de uso del suelo. *Boletín ASAGIR*.

Galantini J., Keine C. 2013. Efectos de largo plazo de la siembra directa en el SO Bonaerense: Producción de los cultivos y balance de nutrientes. *Revista AAPRESID* 2013.

Gil R., Garay A. 1999. "La siembra directa y el funcionamiento sustentable del suelo. *Actas XIV Congreso Latinoamericano de la Ciencia del Suelo*. Pucón, Chile.

Gil R., 2012. Manejo de suelos y uso eficiente del agua. *Revistas Técnicas Aapresid*.

Ministry of Agroindustry. *Statistics and Estimations*. 2016. https://datos.magyp.gob.ar/

Moschler, W.W., G.M. Shear, D.C. Martens, G.D. Jones, and R.R. Wilmouth. *1972*. Comparative yield and fertilizer efficiency of no-tillage and conventionally tilled *corn*. Agronomy Journal 64: 229-231.

Omonode, R.A., D.R. Smith, A. Gál, and T.J. Vyn. 2011. Soil Nitrous Oxide Emissions in Corn following Three Decades of Tillage and Rotation Treatments. *Soil Sci. Soc. Am. J.* 75:152-163.

Paul E.A. 2007. *Soil Microbiology, Ecology and Biochemistry*. Eds.

Pognante, J., Bragachini, M., Casini, C. 2011. *Siembra Directa*. PRECOP II. INTA

Smith, D.R., Warnemuende, E.A., Huang, C., Heatman, G.C., 2007. How does the first year tilling a long-term no-tillage field impact soluble nutrient losses in runoff? *Soil and Tillage Research* 95, 11-18.

Studdert, G., and H. Echeverría. 2000. Crop rotations and nitrogen fertilization to manage soil organic carbon dynamics. *Soil Sci. Soc. Am. J.* 64:1496-1503.

Studdert, G. and H. Echeverría. 2002. Rotaciones mixtas, labranzas y carbono orgánico en la capa arable en el sudeste bonaerense. *En Jornada de Actualización Técnica para Profesionales "Fertilidad 2002"*. INPOFOS Cono Sur. Acassuso, Buenos Aires. 52 pp.

Socioeconomic Impacts of Genetically Modified Crops can be Pro-Poor

Matin Qaim

Introduction

Genetically modified (GM) crops have been grown commercially for more than 20 years in many parts of the world, including in developed and developing countries and by large and small farms. Most of the GM technologies used so far involve herbicide tolerance (HT) and insect resistance (IR) in crops like soybean, maize, cotton, canola, and a few others. In spite of the rapid and widespread adoption of GM crops by farmers in almost all parts of the world, public attitudes remain skeptical, especially in Europe but also elsewhere. Many believe that GM crops are risky for human health and the environment and bring no benefits for farmers and consumers. Numerous scientific studies have shown that GM crops are not more dangerous than conventionally bred crops. There is also a broad body of literature demonstrating sizeable economic and environmental benefits. The problem is that this scientific evidence has not really entered the public debate. Anti-biotech groups were much more successful in influencing public opinions through denying scientific results and spreading their own unsubstantiated narratives about risks and negative social impacts (Qaim 2016).

To be sure, results of scientific studies about GM crop impacts, which were carried out in different countries and with different data and methodologies, vary significantly. Depending on many factors, some studies show higher yield effects, while others show lower or no yield effects at all. Some point at reductions in the use of pesticides, while others point at increases in the use of pesticides and other chemical inputs. Hence, individual studies should not be generalized too widely. Results always depend on the particular context. But what can we learn from looking at the existing body of literature about GM crop impacts more systematically?

Results from a meta-analysis of GM crop impacts

A meta-analysis can help to draw some broader conclusions about mean effects at the global level, and also about reasons for deviations in particular situations. A recent meta-analysis, which we carried out, presents a clear picture: combining results from all scientific studies that compared the performance of GM and conventional crops reveals that GM technology has increased crop yields by 22% and reduced chemical pesticide use by 37% on average (Table 1). GM seeds are usually more expensive than conventional seeds, but the additional seed costs are compensated through savings in chemical pest control and higher revenues from sales. Average profit gains for GM crop-adopting farmers are 68% (Klümper and Qaim 2014).

Table 1. Mean impacts of GM crop adoption in % (meta-analysis results)

Outcome variable	All GM crops	Insect-resistant crops	Herbicide-tolerant crops
Yield	21.57***	24.85***	9.29**
Pesticide quantity	-36.93***	-41.67***	2.43
Pesticide cost	-39.15***	-43.43***	-25.29***
Total production cost	3.25	5.24**	-6.83
Farmer profit	68.21***	68.78***	64.29

, * statistically significant at 5% and 1% level, respectively.
Source: Klümper and Qaim (2014).

A breakdown of GM crop impacts by type of technology reveals a few notable differences (Table 1). While significant reductions in pesticide costs are observed for both HT and IR crops, only IR crops lead to a consistent reduction in pesticide quantity (pesticides, as defined here, include insecticides, herbicides, fungicides, and all other chemical pest control agents). Such disparities are expected, because the two technologies are quite different. IR crops protect themselves against certain insect pests, so that spraying insecticides can be reduced. HT crops, on the other hand, are not protected against pests but against broad-spectrum chemical herbicides (mostly glyphosate), use of which facilitate weed control. While HT crops have reduced herbicide quantity in some situations, they have contributed to increases in the use of broad-spectrum herbicides elsewhere. The savings in pesticide costs for HT crops in spite of higher quantities can be explained by the fact that broad-spectrum herbicides are often much cheaper than the selective herbicides that were used before. Average yield effects are also higher for IR than for HT crops.

In the meta-analysis, we also differentiated between impacts in different countries, finding that farmers in developing countries benefit much more from GM crop adoption than their colleagues in developed countries. The reasons for significantly higher average yield and farmer profit gains in developing countries are twofold. First, farmers operating in tropical and subtropical climates often suffer from more considerable pest damage that can be reduced through GM crop adoption. Hence, effective yield gains tend to be higher than for farmers operating in temperate zones. Second, most GM crops are not patented in developing countries, so that GM seed prices are lower than in developed countries, where patent protection is much more common (Klümper and Qaim 2014).

Aggregate benefits at the global level

Aggregating the economic effects from micro-level impact studies to the total area currently cultivated with HT and IR GM crops results in global farmer benefits of over 20 billion US dollars per year (or more than 150 billion US dollars when using the cumulated adoption rates over the last 20 years). In addition, consumers benefit through lower prices that they pay for food and other agricultural commodities. A new technology with gains in farm productivity reduces market prices to levels lower than they would be without the technology. Hence, consumers also gain from productivity-increasing technology.

GM crops have also contributed to positive environmental effects. Reductions in the use chemical pesticides have led to benefits for biodiversity and ecosystem functions (Veettil et al. 2017). As mentioned, pesticide reductions are particularly relevant for IR crops. HT crops have facilitated the adoption of reduced-tillage practices, thus reducing erosion problems and greenhouse gas emissions from the soil. Finally, without the productivity gains from GM crops, around 25 million hectares of additional farmland would have to be cultivated globally, in order to maintain current agricultural production levels (Qaim 2016). As is well known, farmland expansion into natural habitats is an important contributing factor to biodiversity loss and climate change.

Effects for smallholder farmers in developing countries

GM crop adoption in developing countries has also led to social benefits. Especially IR cotton is widely grown by smallholder farmers in countries like China, India, Pakistan, Burkina Faso, and South Africa. With my research group we have studied the situation in India over many years. More than 90% of the cotton growers in India have switched to GM technology. Higher yields and profits have contributed to significant welfare gains in smallholder households. Our estimates with panel data show that the adoption of IR cotton has raised household living standards by 18% on average (Kathage and Qaim 2012).

Higher family incomes through IR cotton adoption in India have also caused improvements in dietary quality and nutrition (Figure 1). Our data suggest that GM technology adoption has reduced food insecurity among Indian cotton growers by 15-20% (Qaim and Kouser 2013). Beyond the cotton growers themselves, other rural households benefit from growth in the cotton sector through additional employment (Subramanian and Qaim 2010). This is particularly relevant for poor landless families. Two-thirds of all rural income gains from GM cotton adoption in India accrue to poor people with incomes of less than 2 dollars a day (Figure 2).

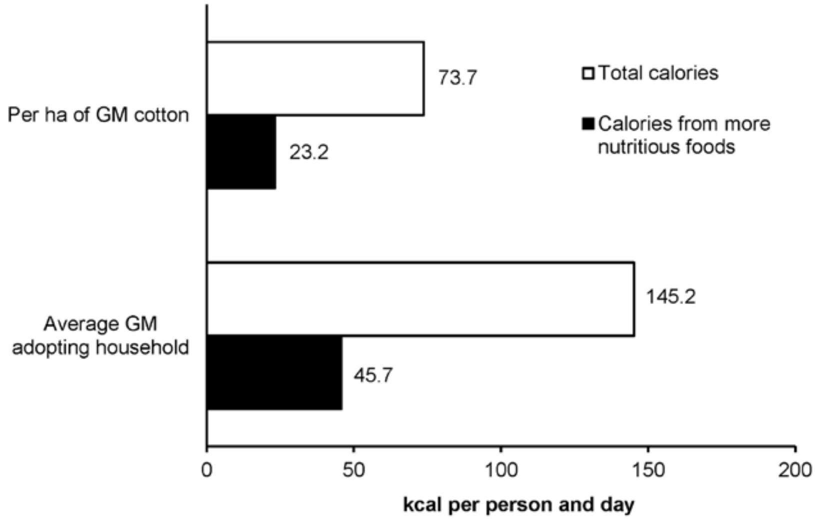


Figure 1. Nutrition effects of GM cotton adoption among Indian smallholder farm households. Net effects of adoption on total calorie consumption and calories from more nutritious foods (pulses, fruits, vegetables, animal products). Source: Own preparation based on data from Qaim and Kouser (2013).

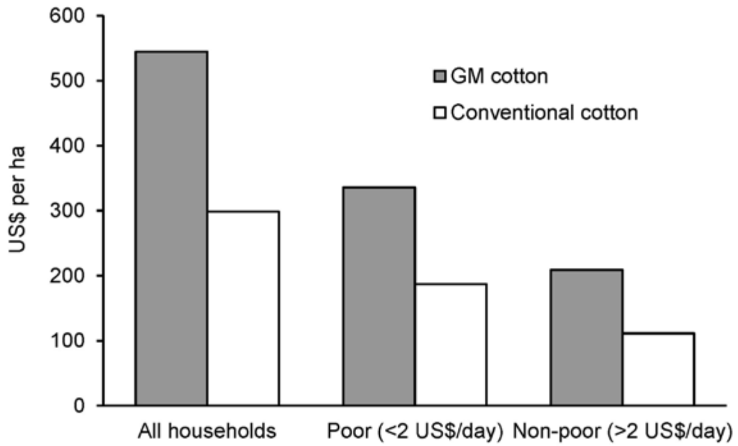


Figure 2. Poor households benefit more from GM cotton adoption than non-poor households in rural India. Source: Own preparation based on data from Subramanian and Qaim (2010).

Similar to these results from India, GM cotton has contributed to poverty reduction and other social benefits in the small farm sectors of China and Pakistan (Huang et al. 2010, Kouser et al. 2017). These positive effects of GM cotton have increased over time (Qaim 2016).

Future prospects

This evidence on impacts from around the world suggests that GM crops promote sustainable development in terms of all three sustainability dimensions, that is, economically, socially, and environmentally. With HT and IR traits introduced in only a handful of crops, the range of commercialized GM technologies is still limited. The main reasons for this narrow focus are public resistance against GM crops and overregulation, leading to long and unpredictable processes for technology approval. Many other promising GM technologies have been developed and successfully tested in various countries, so far without getting the commercial go-ahead. Cases in point are GM traits such as fungal and virus resistance, drought and salt tolerance, higher nitrogen use efficiency, and higher micronutrient contents in food crops such as rice, wheat, sorghum, cassava, potato, banana, and various vegetables. The potentials of such technologies to contribute to poverty reduction and food security in developing countries are large (Qaim 2016).

This does not mean that GM crops cannot also lead to undesirable effects under particular conditions. Every technology may cause certain problems if misused or not managed properly. For instance, GM crops have contributed to a rising concentration in biotech and seed industries. More efficient regulation could help to reduce or avoid issues of market power. Several weed species in North and South America have developed resistance to glyphosate, because the same HT crops were grown year after year. Reducing resistance development requires improved agronomy, especially better crop and herbicide rotations. These problems need to be addressed, but they hardly justify banning GM crops, as some anti-biotech groups call for. For comparison, we also observe market concentration in software and internet-based industries, without banning computers and the worldwide web. And we also observe the development of resistance to antibiotics in various human pathogens, without broadly prohibiting the use of antibiotics from all medical applications. In organic agriculture, the use of copper as a non-synthetic agent to control fungal diseases can cause serious environmental problems, without calls for banning organic farming practices altogether. When we are serious about sustainable development, we need to be more open-minded and stop judging technologies with very different standards.

References

Huang, J., et al. (2010). A Decade of Bt Cotton in Chinese Fields: Assessing the Direct Effects and Indirect Externalities of Bt Cotton Adoption in China. *Science China Life Sciences* 53: 981-991.

Kathage, J., Qaim, M. (2012). Economic Impacts and Impact Dynamics of Bt (*Bacillus thuringiensis*) Cotton in India. *Proceedings of the National Academy of Sciences USA* 109, 11652-11656.

Kouser, S., Abedullah, Qaim, M. (2017). Bt Cotton and Employment Effects for Female Agricultural Laborers in Pakistan. *New Biotechnology* 34, 40-46.

Klümper, W., Qaim, M. (2014). A Meta-Analysis of the Impacts of Genetically Modified Crops. *PLOS ONE* 9(11), e111629, http://dx.plos.org/10.1371/journal.pone.0111629.

Qaim, M. (2016). *Genetically Modified Crops and Agricultural Development*. Palgrave Macmillan, New York.

Qaim, M., Kouser, S. (2013). Genetically Modified Crops and Food Security. *PLOS ONE* 8(6), e64879, http://dx.plos.org/10.1371/journal.pone.0064879.

Subramanian, A., Qaim, M. (2010). The Impact of Bt Cotton on Poor Households in Rural India. *Journal of Development Studies* 46, 295-311.

Veettil, P.C., Krishna, V.V., Qaim, M. (2017). Ecosystem Impacts of Pesticide Reductions through Bt Cotton Adoption. *Australian Journal of Agricultural and Resource Economics* 61, 115-134.

The Role of Plant Biotechnology in Human Health. Public Sector Constraints: The Golden Rice Experience

Adrian Dubock

When agriculture started about 12,000 years ago, the human population was 3 million people. With around 250,000 (net) additional people every day, it will be ~9 billion in 30 years. Agriculture has the biggest negative impact on biodiversity. And intensive agriculture is the kindest for maintenance of biodiversity by protection of wild lands from food production. Despite the population growing exponentially, farmers have managed to keep food production – yield of the macronutrients carbohydrate and protein – ahead of human population increase by plant breeding, and in the last century by using inorganic fertilizers and chemical pesticides.

Nevertheless, the 2016 G20 Agriculture Ministers remained "deeply concerned that, despite tremendous efforts, 795 million people in the world still suffer from chronic hunger and 2 billion people from [micronutrient] malnutrition" (1).

Food production needs to double by 2050 due to population growth, yet only around 15% of the land area is suitable for food production with current technology (2). And not only macronutrients but also micronutrients – minerals which plants obtain from the soil, and vitamins synthesised by plants or animals – are essential for human development and health. A sufficient source of vitamin A is very important for sight and life. Vitamin A deficiency (VAD) is very common in developing countries and globally the most significant cause of irreversible childhood blindness. In 2014 VAD killed between 1.4 and 2.1 million young children, despite all existing interventions and 25 years UN attention. These preventable deaths are greater than the total death toll from HIV/AIDS or TB or malaria (3) (or Ebola ~13,000 in 2014-5).

The World Food Prize 2016 was awarded to the team involved with the introduction of orange-fleshed sweet potato as a vitamin A deficiency intervention (4). The Director of 'Harvest Plus', and one of the laureates is Dr Bouis. Before Harvest Plus started its activities in 2003, Dr Bouis had already joined the Golden Rice Humanitarian Board.

Golden Rice, a 'GMO-crop' was created by incorporating in the rice genome two non-rice genes. This occurred once, in around 2004 (5), the year the Cartagena Protocol (6) came into force. In the same year, rice was providing the global population with 2,000,000 million calories per day. Sweet potato was providing less than 2% as many (7).

How can it be that Harvest Plus, which started operations in 2003, has been successful, and Golden Rice, initially created in 1999 (8) has not yet even been grown by farmers by 2016?

The June 1992 Earth Summit in Brazil, the first UN Summit meeting to include non-governmental representatives, agreed 27 Principles which became The UN Convention on Biodiversity ('CBD'). Principle 1 is that:

Human beings are at the centre of concerns for sustainable development.

They are entitled to a healthy and productive life in harmony with nature.

Principle 15 is that:

In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.

This 'precautionary principle' has long been a major impediment to good sense in public policy … it has been an invaluable tool for those who want to stop any new scientific development that they dislike" (9).

Greenpeace have been long-standing opponents of GMO-crops. They were involved in 1992 in Rio and subsequently boasted that "we won almost all the points we were pushing for" (10) in the writing of the Cartagena Protocol.

Principle 15 of the Rio Declaration became Objective 1 of the Cartagena Protocol, the basis of national regulatory systems for GMO-crops worldwide, which insist first of all on generation of molecular data. A plant breeder can much more quickly, and cheaply, decide if a plant has useful characteristics or not. But in the system which Greenpeace takes pride in, traditional plant breeders work in the field is delayed for several years.

Greenpeace have cynically ignored scientific evidence about GMO crops for fundraising purposes by suggesting that GMO-crops are a unique class of agricultural product, despite longstanding scientific agreement that they are not (11,12,13) Even large organisations, public and private, have actively avoided GMO-crop-controversy-entanglement (14). Individual scientists have been distracted from their work (15).

Activist organisations such as Greenpeace have also promulgated the view that GMO-crops are dangerous to human and environmental health, are solely for use in industrialised countries for 'evil' multinational company profit and provide no consumer benefit.

Greenpeace's narrative is false (Golden Rice is one example of why, and there should be many more) (16). Nevertheless, Greenpeace's false narrative has misled some, and intimidated many organisations in the public and private sector, who wished to avoid the anticipated controversy.

Paradoxically the activists' success has induced the creation of that which they oppose: only multinational companies can afford the costs and complexities of registration of GMO-crops. The result of Greenpeace's influence has been to reinforce commercial oligopoly for major industrial crops which they purport to object to. The public sector and small companies usually cannot compete.

One of the reasons Harvest Plus has been so successful is that they adopted a 'no-GMO-crop' strategy (17) from 2003 purposefully to avoid "the hurdles and criticism", and so successfully raised extensive operational funding, including from some similarly intimidated sources. However, Harvest Plus have also noted that conventional seed breeding techniques cannot achieve success with increasing iron and zinc in rice, and recently, they have acknowledged that only with precision agriculture, using transgenesis to create GMO-crops, have they achieved success with these traits (18). Increases of not only iron and zinc, but also folate and pro-vitamin A in staple crops of the poor are all extremely important for human health. All have been achieved using GMO-technology, where conventional breeding was not possible.

The public sector holds the responsibility for public health delivery through biofortification of food security crops. For biofortification especially, plant breeders need rapidly to catch up with the 12,000-year head start of seed breeding for yield. Precision agriculture, including GMO-crops now provides the tools to assist, both for macronutrients, to adapt yields to climate change and other difficult growing conditions, as well as micronutrients. Most farmers using GMO-crops in 2014 – clearly of their free will – did so on small farms in developing countries (19).

Religious leaders, the UN, and Governments have an important leadership role to encourage the use of all plant breeding tools, without ideological overlay, to deliver the food we need. For the sake of humanity, and the environment, Greenpeace should not hinder the applications of Precision Agriculture.

References

1. http://www.g20.utoronto.ca/2016/160603-agriculture.html
2. http://www.nasaconline.org/dmdocuments/agric-biotech-conf/Agricultural%20biotechnology%20in%20Europe%20and%20Africa-Anne%20Glover.pdf (primary source not found)
3. Dubock, A. (2016), 'Biofortified Golden Rice as additional intervention for Vitamin A deficiency (VAD)', in Sasaki, T. (ed.), Achieving sustainable cultivation of rice. Volume 1: breeding for higher quality, Burleigh Dodds Science Publishing Limited, Cambridge, United Kingdom (ISBN: 978 1 78676 024 1; www.bdspublishing.com).
4. https://www.worldfoodprize.org/en/laureates/2016__andrade_mwanga_low_and_bouis/
5. Paine et al., Paine, J., Shipton, C., Chaggar, S., Howells, R., Kennedy, M., Vernon, G., Wright, S., Hinchliffe, E., Adams, J., Silverstone, A. and Drake, R. 2005. Improving the nutritional value of Golden Rice through increased pro-vitamin A content. *Nature Biotechnology*, 23(4), pp. 482-7.
6. https://www.cbd.int/doc/legal/cartagena-protocol-en.pdf
7. Harvest Plus data
8. 2000, Ye, X., et al. Engineering the provitamin A (beta-carotene) biosynthetic pathway into (carotenoid-free) rice endosperm. *Science (New York, NY)*, 287(5451), pp. 303-5.
9. 2007 http://www.prospectmagazine.co.uk/features/therealgmfoodscandal
10. 2000 http://scholarlycommons.law.case.edu/cgi/viewcontent.cgi?article=1189&context=faculty_publications
11. 2000 http://www.nap.edu/catalog.php?record_id=9889
12. 2016 https://nas-sites.org/ge-crops/
13. 2016 https://royalsociety.org/topics-policy/projects/gm-plants/
14. Dubock, A.C., 2014a0. The politics of Golden Rice. *GM Crops & Food 5:3, 210–222; July/August/September 2014.* Available at: http://www.goldenrice.org/PDFs/Dubock-The_present_status_of_Golden_Rice-2014.pdf
15. Dubock, A.C., 2014b. The present status of Golden Rice. *Journal of Huazhong Agricultural University*, 33(6), pp. 69-84.
16. 2016 http://supportprecisionagriculture.org/
17. 2011 http://www.theecologist.org/News/news_analysis/1159571/can_gmfree_biofortified_crops_succeed_after_golden_rice_controversy.html
18. 2016 https://www.genetic-literacyproject.org/2016/02/16/newgmoricecouldfightironzincdeficienciesindevelopingworld/
19. 2015 https://www.isaaa.org/resources/publications/briefs/49/executivesummary/pdf/B49-ExecSum-English.pdf

The Nobel Laureates' Campaign in Favor of GMOs

Richard J. Roberts[1]

In this talk, I will describe the Nobel Laureates' Campaign in support of GMOs (Genetically Modified Organisms) and touch on a few key points that highlight the reasons why GMOs are important and mention some of the misleading statements that the anti-GMO activists use to try and discredit this technology, which arguably is one of the most exciting outcomes of the modern biotechnological revolution.

Let me begin by explaining how I came to start this campaign. I was invited to a Symposium in Ghent four years ago (2013) celebrating the 80th birthday of Marc von Montagu (World Food Prize Winner and one of the inventors of the GM method). The result was that I spent a day listening to people talk about plants and in particular, hearing people talking about the difficulties that they faced as a result of opposition from the Green Parties. Frankly, I found it hard to believe what I was hearing. I had read a little about it, but I just couldn't believe how bad things really were. The next day I had been invited to talk to the European Commission about the future of medicine and had originally planned to speak of some of the major lines of research such as the advances in cancer immunotherapy that were looking extremely promising. However, I decided to change the topic of my talk the night before and instead made GMOs the theme of my talk.

I started by explaining that medicine for developing countries was rather different from medicine for developed countries. I pointed out that in addition to needing all of the things that we usually think of such as vaccines, common drugs and basic care, the thing that they most cared about in many countries was food. People who go to bed hungry at night, don't really worry so much about medicine, but they do worry about food and whether they are going to have a good meal inside them. Of course, food means agriculture.

For the last 10-12,000 years, since agriculture first got started in the Middle East, things were pretty crude – people went out and gathered the plants they could and put them in the backyard and hoped they would

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grow, and then they started to figure out how to cross them and how to make better breeds and so on, but in the 1980s thanks to Marc van Montagu, Jeff Schell and Mary-Dell Chilton it suddenly became possible to manipulate these plants and to enhance breeding possibilities in a way that was far more precise and far simpler than had been available previously.

So, what I decided to do after the talk was to try and mobilize the Nobel Laureates to support GMOs and counter the misleading statements being propagated by the Green parties. Of all of us, there was not a single Nobel Laureate who was a professional plant scientist. There were a couple who had distant connections to industry, but all of the scientists who had previously been talking about plants usually had connections to agri-business and were criticized heavily for it as being compromised. Of course, the reason they had agri-business ties was because very often governments wouldn't support them. Government support for academic plant research has been pretty pathetic. However, the big agri-businesses had been interested in the results of their research and so were prepared to support them. And of course as soon as you get money from business, along come Greenpeace and the Green Parties and they say well, we can't believe anything you say because you are tainted by industry. However, apparently, they themselves are not tainted by contributions from the organic farming industry.

In the U.S., another problem came because of the Freedom of Information Act, which allowed the anti-GMO people to request documents and emails from scientists working at public universities about their GMO plant work. These have to be made available and then the opponents select those parts that they can use to tell a misleading and inaccurate story and harass the scientists in ways that I think most of us who are not in the field can't imagine. But when you ask plant scientists who speak about GMOs then they will tell you exactly what's going on – how they are constantly harassed because of their Pro-science statements.

So, it was really after Marc's birthday party that I started to think about this issue, but it wasn't until 2015 that I decided to get going and start to recruit the Nobel Laureates to support GMOs. I had some ideas of what a campaign might look like and so when I went to a Lindau meeting in southern Germany where there are a lot of Laureates, I began asking them how they felt about GMOs and the idea of a campaign. With just one exception, every Laureate who was at that meeting said this was a great idea and would like to join. This led to about 20 initial signatures just from that one meeting and then I began to send out requests to other Laureates. Eventually, I collected about 100 signatures, which I thought was a respectable number of Nobel Laureates for a campaign and decided to launch it. We held a press conference in Washington, DC on June 30th 2016 that received a lot of publicity. More than 25,000 blogs and news articles came out almost immediately following the news conference. The idea was that here we were, a group of Nobel Laureates that have good credibility with a lot of people including the general public. We are listened to and taken seriously. In particular, we thought we were reasonably immune from the usual attacks from Greenpeace because we didn't have any connections with agri-business.

Just before the press conference I sent a fax to Greenpeace and to every United Nations Ambassador, calling on them to stop scaring the public by pretending that GMO foods were dangerous. *Please stop making all of these misleading statements, which you know are false, because after more than 20 years of the use of GMO products in the field there is not a single case of an accident or any problem that can be honestly attributed to GMOs.* The time had come for Greenpeace and the Green Parties to admit this was one issue that they just got wrong. Perhaps, when they started their activism they could argue they were right to draw attention to the possible problems, but by now they know the fears are groundless. But instead of acknowledging they were simply wrong in claiming GMOs are dangerous they are now trying to spread this fear of GMOs to the developing world. Figure 1 is a cartoon that I use to illustrate the problems the activists are now causing. It's by a

Figure 1.

man called Brian Duffy, who resides in Iowa. I think it's rather good – on the left is Greenpeace who are portraying GMO foods as being really dangerous, calling them Frankenfood. In contrast on the right is a hungry little boy who truly appreciates the value of GMO foods. I find it very difficult to look at this cartoon and not feel that you know here is a technology, which can help the developing world in major ways. Why would anybody be against it?

If we think about what has happened in agriculture since it was first developed, how man's efforts to breed better crops have resulted in the foods we consume today, it is clear that crop improvement has been essential for our welfare. One example is provided on in the left panel of Figure 2, where the original ancestor of corn, called teosinte, was slowly bred from its original very thin and stringy cob to the good-looking and healthy corn cob on the right. In the right panel is a cartoon I love from the *New Yorker,* which shows a very happy big corn cob and the lady is wondering which is the genetically modified corn. I think it is not difficult to figure out which that should be.

When I give talks in this area I always try to find analogies that will be easily understood and that will be immediately comprehensible to people who know little or nothing about the science of genetics. The approach I use is to begin by talking about the traditional methods of breeding. For instance, improved plants can be made by mixing the genes in the same way we make babies. Two people get together and they produce an embryo, which is a mix of the genes in the two parents. This is the old-fashioned or traditional method of plant breeding. In the case of plants if one

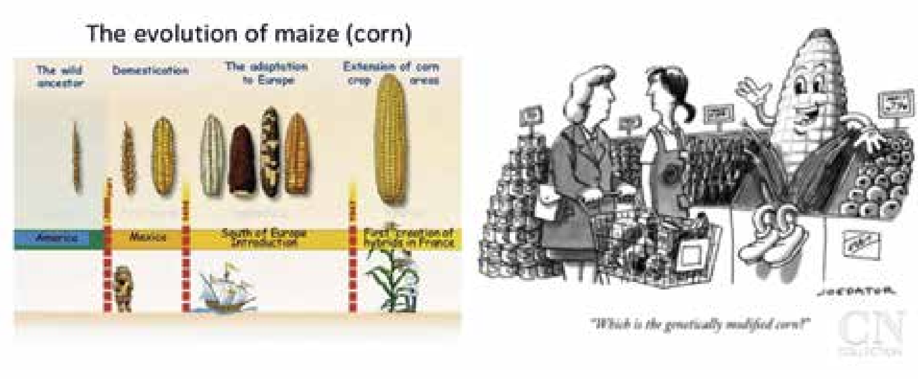

Figure 2.

of the parents has a trait (perhaps caused by one gene) that is desired, then we can look at the offspring and just select the ones that have this trait. By constantly crossing back to the original, preferred parent plant, then we can slowly eliminate the genes we don't want while retaining the gene we do want. Now though, we know that thanks to the GMO approach we can simply identify the gene responsible for the trait we want and move it directly into the preferred parent plant.

One analogy I have found very effective concerns how one might move a GPS system from one car to another. Do I take the cars apart, mix the components and then put everything back together and hope that I'm going to get something that works, or do I just take the GPS from one car and move it into the other car? The precision method of plant breeding looks exactly like taking the GPS from one car and moving it to another. I always then ask, "Do you know, Greenpeace would have you believe that if I took the GPS system from an airplane and put it in the car, now it's going to fly". And Greenpeace is also claiming that all flights inescapably end in crashes. We all know that is just nonsense. This is typical of the misleading information that they're putting out and through which they have been very successful in scaring the public and in raising funds to support their activities. But the problem is once people get scared, it is very, very difficult to reassure them. At this point it's all about emotion. It's about fear and not about facts and it's certainly not about science. The science is clear, the science is safe,

Figure 3.

Figure 4.

the science says everything is good and it's all about how we deal with these emotional issues. Of course we always feel as scientists that all we have to do is explain the science to everybody and they'll understand it and realize they have no reason to be scared. Unfortunately, it's not enough. Just explaining the science doesn't usually work. Consequently, I like to try an additional approach of pointing out that what is important is the product.

GM (genetic modification) refers to a method; it's a way of doing something. We've been genetically manipulating plants for many thousands of years. There is very little that we eat that has not been genetically modified by so-called traditional or "natural" methods, but it is hard to understand how deliberate mutation is natural! But now we've learned how to breed plants in a much more precise way, but it is very important to remember that it is the product of plant breeding that is key not the method by which the breeding took place. This is also true for traditional breeding and it's important that we remember that. Again, I have an analogy. Figure 3 shows a production line that is making a means of transportation, but what is it making? Well two options are shown in Figure 4, one is a car, another is a tank, but it could easily be something else. We cannot gauge the beneficial or harmful results on the product just based on how the production is being carried out. The product is what matters here, not the way in which we made it. I think we can all agree that if you want to be driving down the highway you'd prefer the car, rather than the tank. We should neither condemn nor praise the product just on the way it is produced. So with traditional plant breeding and GMO methods, it is the product that is im-

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Many common vegetables have high levels of natural pesticides.

Dietary pesticides (99.99% all natural)*

(carcinogens/mutagens/clastogens/coffee)

BRUCE N. AMES†‡, MARGIE PROFET†, AND LOIS SWIRSKY GOLD†§

Table 2. Some natural pesticide carcinogens in food

Rodent carcinogen	Conc., ppm	Plant food
5-/8-Methoxypsoralen	14	Parsley
	32	Parsnip, cooked
	0.8	Celery
	6.2	Celery, new cultivar
	25	Celery, stressed
p-Hydrazinobenzoate	11	Mushrooms
Glutamyl *p*-hydrazinobenzoate	42	Mushrooms
Sinigrin* (allyl isothiocyanate)	35–590	Cabbage
	250–788	Collard greens
	12–66	Cauliflower
	110–1,560	Brussels sprouts
	16,000–72,000	Mustard (brown)
	4,500	Horseradish

+ 11 more

Figure 5.

portant and that needs to be tested. A label saying it has been produced by a GMO method tells us nothing useful about the product.

To illustrate the importance of testing products and not just the methods by which they arise there are many examples in the plant world where traditional breeding, widely considered perfectly safe, has resulted in plants with harmful chemicals in them. Plants have one major obstacle to their existence – they cannot run away when a predator comes along wanting to eat them. So their solution has been to evolve to produce pesticides that will kill their predators; chemical warfare. This means that if you look in almost any plant you will find a lot of chemicals that act as natural pesticides as exemplified in Figure 5. In some cases, these chemicals are also carcinogenic to humans. One good example is celery. If you cut up celery and don't wear gloves, you will get celery juice on your hands. People who used to harvest celery or cut it up in preparation for sale, would often find they were developing a skin dermatitis that would occasionally turn into skin cancer. This is because of some carcinogens, notably psoralen, that are naturally present in celery. But we all eat celery so why don't we all get cancer from it? The reason is that the quantities are very small. If your entire diet was celery, you'd be in trouble. But it's not. Our bodies know how to deal with small quantities of many dangerous chemicals, psoralen included. The lesson here is that what is important is what are the ingredients in the food we eat and in what quantities. It does not matter whether the plants have been bred by traditional means or by the more precise methods using GM techniques. In the case of celery any organic farmer or any member of Greenpeace would tell you it is perfectly safe, you don't need to worry about it. It's natural, and so it must be okay. This is just wrong-headed and unscientific thinking. I'm inclined to think that if we are going to do something about regulating foods, then we have got to examine the product and forget about the method by which it was generated. The methods don't matter at all.

You might ask why did Europe get behind the "GMOs are dangerous" movement? Well history can give us some clues. In Europe and the USA, we don't need GMOs. We have plenty of food because the major agri-businesses have focused almost all of their breeding efforts on crops we consume in the developed world and where high profits can be made. As a result, we are all well-fed to a point of often being overfed. You don't see a lot of thin Europeans walking around unless they are recent immigrants from Africa. And so why doesn't Europe endorse GMOs? You know, it makes no difference to us and so I ask is it politics, is it money, or is it both – and I think the answer is that it's both. The real problem is that the Europeans didn't want U.S. companies to control their food. So how could they stop that? Well, of course the easy thing to do would be to ban Monsanto and the other American agri-businesses. But there lies a major problem. In Europe an awful lot of seeds that have been produced by traditional breeding are bought from U.S. companies. And so if we say we're not going to buy them anymore, then we really will start to see some thin Europeans. So a direct ban was not possible. So what did the Europeans do? They began arguing that precision agriculture, or GMOs must be dangerous and so they should be banned from Europe. This would indirectly affect the American agri-businesses and given that GMO technology was spreading and was likely to be very profitable it would hurt their bottom line. Thus began a campaign by the anti-GMO activists to discredit GMO technology. They would make up stories up about the possible dangers of these "Frankenfoods". It was very easy to think of horror stories based on moving genes from one source to another. It becomes simple to imagine dire consequences. If I take genes from a salmon and put them into a plant, then perhaps the plant will start swimming. Equally crazy stories were manufactured with the deliberate intention of scaring people.

And of course they had very good advertising agencies working for them and I think you know as well as I do that a good advertising firm can sell pretty much anything. When the plant scientists tried to defend themselves from this they didn't stand a chance because they lacked the money to pay for the same quality of advertising. The result was that Greenpeace were incredibly successful in scaring everybody. This led to financial support from their donors to help demonize GMOs and then they were able to gain political power using the well-worn technique of identifying a danger and then saying "we will protect you from the danger, vote for us". In this way Greenpeace gained both political power and they also gained money. They became one of the richest NGOs with an annual budget in excess of $500 million a year. And the real beauty of this approach was that a ban on GMOs would have few economic consequences for Europe. Europe didn't need GMOs – they already had more food than they could eat.

However, it turns out that in the developing world there is a desperate need for crops with higher yields, higher nutritional value and the ability to grow under drought conditions. They have not had the benefit of big agri-businesses improving the crops they like to eat. Thus, the really tragic consequence of the anti-GMO parties' declaration that GMOs should be banned is they took this same message abroad (Figure 6). They couldn't say that all GMOs are dangerous only in Europe, but they are perfectly fine for the developing countries. So now we have the situation where European activists are going around the world telling the developing countries that GMOs are dangerous there too. This has reached the point where they are now causing serious harm to people in the developing world by trying

Figure 6.

to deny them the benefits of better crops prepared using GM methods and grown widely in the Americas and Australia, imported and consumed around the world. This is both ridiculous and frightening. We MUST find a way to stop it. All of the major professional scientific societies have come out and said that GMOs pose no danger (Figure 7). The only people who are negative are the people who were anti-GMO to start with and in general they have no credible scientists associated with them. My feeling on this, and one of the sentiments that was expressed in the letter that the Nobel Laureates sent to Greenpeace and every U.N. Ambassadors was this: How many people and especially how many kids have to die before we consider this anti-GMO movement to be a Crime Against Humanity? I believe we've already gone way past that point. I think what the anti-GMO activists are doing is criminal and they have to be stopped. It is time for Greenpeace and their allies to admit that they made a mistake when they began their opposition to GMOs. We now have almost 30 years of experience in the area and the science is clear. Some of their former leaders have done this; it is time for the rest to follow. The method is not "dangerous" and if anything is "safer" than traditional plant breeding.

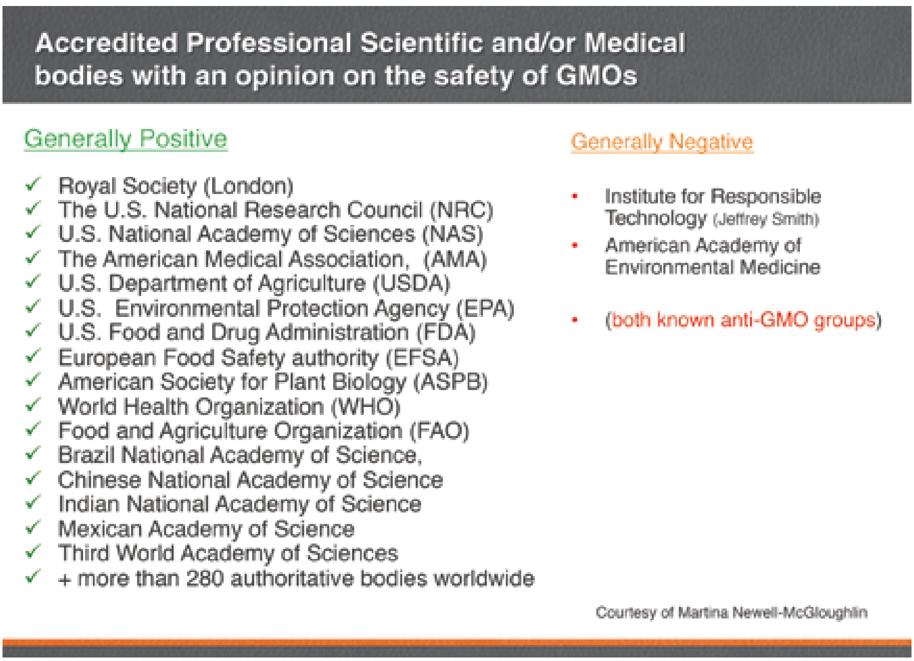

Figure 7.

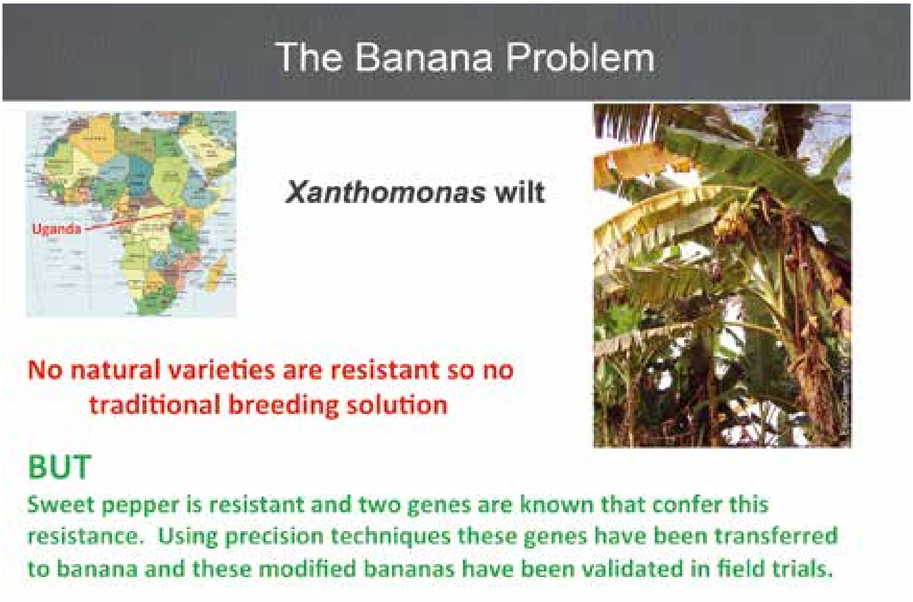

Figure 8.

There are several important projects that are underway. One concerns bananas in Uganda (Figure 8). The bananas have a particularly interesting problem that is very difficult to deal with. They have a disease called *Xanthomonas* wilt for which there is no known non-GMO solution. There is no way of fixing this by traditional breeding, but there's a beautiful GMO solution. It turns out that sweet pepper is naturally resistant and there are two genes that are responsible for the resistance. Ugandan scientists have put these genes into bananas and the bananas are now resistant to *Xanthomonas* wilt. This is perfect, because 30% of the calories in the diet of Ugandans come from bananas (which they call "matoke") and in many other parts of sub-Saharan Africa this is also a very important food source.

Another interesting case concerns papayas, which are already being produced from GM plants for many years in Hawaii, because this was the only way to combat a disease caused by a ringspot virus (Figure 9). As you may know there has been as a strong movement in the USA and elsewhere to label foods containing GM ingredients. When this issue came up in Hawaii and the politicians wanted to introduce laws saying that GMO crops could not be grown, the farmers were up in arms. They protested vigorously arguing it would destroy their ability to export their papayas. So what did the

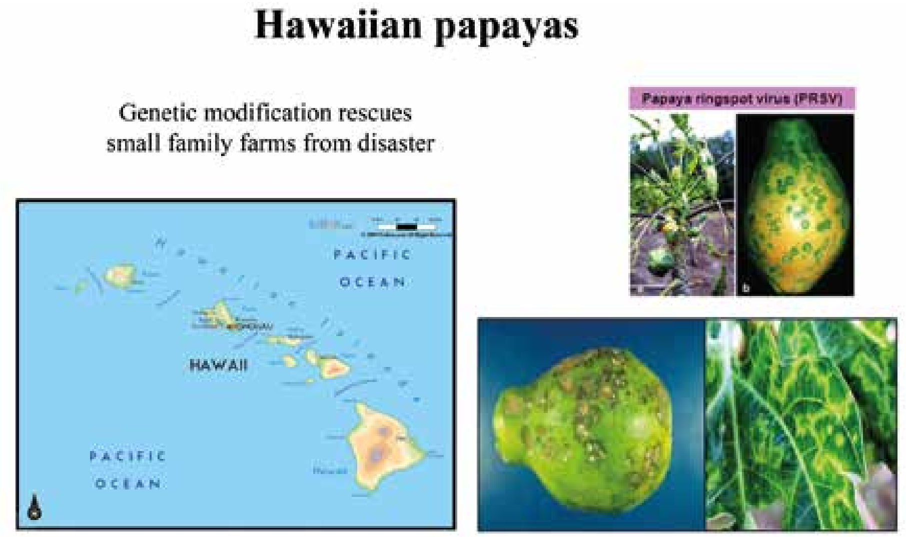

Figure 9.

politicians do? They said they would "grandfather" papayas and exclude them from the laws thereby pretending they were not GMOs. Only the newly developed GM crops would have to be labeled. So, GMO papaya wound up saving the Hawaiian crop and now 77% of all the papayas that we eat in the US are GM, with no problems having been reported. In Thailand the same ringspot virus is also causing problems, the GM solution is banned and so what have the farmers been doing in Thailand? They have been getting the GM papaya plants on the black market from a local University laboratory and then growing the GM papayas on their farms without telling the government.

The take home message from this talk should be that we have been genetically modifying crops for tens of thousands of years, without excessive regulation and without the paranoia that has been created by environmental activists and is now surrounding GM crops. The so-called GM method that the activists are so concerned about is just the latest improvement in plant methods to enhance the productivity of the crops that form the basis of our food supply. It is time to realize that if you don't want to eat foods that are derived by GM methods, well that's your choice, but recognize it's a choice. Don't pretend that they're dangerous because if anything, they are probably safer than traditional foods. You know, traditional foods are never tested for all of the things that one has to test for if you are looking at GM

Figure 10.

foods. For most developed countries food isn't a problem, but for much of the developing world it is. When we make statements about the dangers or otherwise of food here we must remember that those statements are quickly transmitted around the world and can have disastrous consequences for the populations there. We can't pretend that disingenuous claims about the safety of food are just for our own political purposes. We need to make sure there's a lot more science in politics and ideally, less politics in science. Politicians should listen to the scientific community. If they are not going to listen to us, why do they fund us to do the research? They should listen to what comes out. Stop pretending that GMOs are dangerous. I don't know if any of you have seen paragraph 72 from the EU report, urging G8 member states not to support GMO crop development in Africa (Figure 10). To try and get such an article into the European constitution is bordering on criminal behaviour as far as I am concerned. Africa of all places is in desperate need of the improved crops that can be generated by GM methods.

I think civil society outside of politics has to play its role too. I think it's important for the major religious leaders to speak out and this is why I am pursuing an opportunity to talk directly to Pope Francis and to persuade him that he should say something very positive here. I talked earlier this year to the leader of the Chinese Buddhists, at a big convention in China. The Buddhists are 100% behind GMOs, but I am still trying to figure out how to get them to make a statement on the issue. But I think there are many religions that should come out and speak about the importance of

Figure 11.

GM technology to help the poor around the world. These are leaders who in principal support the poor, they want the poor to do well and they should do everything they possibly can to make sure they live healthy lives.

The Rotary Clubs also present an interesting opportunity. I've spoken to several rotary clubs now and they are very interested in this issue and I am hoping that support for GM technology will become a major agenda item for Rotary International. That would be huge because Rotary clubs are around the world and they specialize in trying to help the poor. It would also be good if influential celebrities would speak out in favor of GMOs; we certainly need to make sure that the media do a much better job than they did with a recent article in the *New York Times* which was appalling in its dismissal of scientific fact. I actually wrote to the editors of the *New York Times* and suggested that they might want to meet with some of the Laureates and myself and discuss this. Additionally, I think we have to make sure that knowledgeable plant scientists do not get silenced. They are the people who know most about plants and many are very articulate. They are good at explaining what's going on and can put the modern GM methods into the perspective of other methods that have been used over the millennia. We have to help them when they get attacked by Greenpeace and my hope is that many of them will join the Nobel campaign and use us to provide them with some protection.

Finally, Figure 11 is my message to Greenpeace that says "Have a Heart". You know as well as any of us that avoiding GMO foods are a western indulgence of the rich. When you look at the little boy on the left, he's obviously well fed and has plenty of money to buy food. He has a choice in what food to buy. But the boy on the right has neither money nor much choice in his food. Non-GMO just doesn't work for the poor in the developing countries.

Summary and Statement

Thirty-five Academicians attended the Pontifical Academy of Sciences (PAS) Plenary Session on 25-29 November 2016. Thirty-one of them contributed to the proceedings with a lecture in their scientific area of expertise. In order to enrich the program, three half-day sessions were devoted to the fields of *Cosmology*, *Energy* and *Food and Nutrition*. These special sessions were enriched by lectures delivered by seventeen invited scientists, who are not members of PAS, who were also invited to attend other sessions of the scientific program. The special session on *Cosmology* was devoted to the memory of the fiftieth anniversary of Msgr. Georges Lemaître's death, who was PAS President from 1960 until 1966. The special session on *Energy* provided welcome insights into more sustainable sources of energy, made possible by the technological applications of acquired scientific knowledge. Similarly, the special session on *Food and Nutrition and the Role of Biotechnology in Agriculture* provided increasing knowledge on the effects on health of our daily diets and how these contribute to medical progress, an increase in human health and longer lifespans.

At the Opening Session, several Academicians recalled the importance of sustainability and our long-term responsibility to protect our varied environment. This is essential to insure appropriate living conditions for many generations of human beings within the rich diversity of living organisms and their appropriate habitats. We can expect to further benefit from increasing scientific knowledge and its responsible technological applications. Recently developed research methods offer timely possibilities to obtain novel insights into the laws of natural development. For example, they enable a better understanding of the neurological functions of higher animals and, in particular, of human beings. Neurobiologists consider their acquired knowledge as essential in the field of education, also providing long-term forecasts for maintaining appropriate living conditions for humankind in the future.

Furthermore, recently developed research methodologies also enable astrophysicists to obtain deeper insights into the tremendous size of the Universe and into the historical development and life times of solar systems with their planets. We can now expect that the search for existing planets with appropriate conditions to host living organisms may eventually lead to discovering whether life – and what kind of life – exists on distant exoplanets. Such knowledge would represent an important contribution to cosmology and to our worldview.

The scientific basis for the understanding of living organisms is their capacity both to propagate and to slowly undergo evolution at the population level. The driving force of biological evolution is the occasional occurrence of spontaneous mutagenesis in one individual of a population. Both the parental forms and their mutants are steadily submitted to Darwinian natural selection. New insights into molecular mechanisms of genetic variation revealed several natural strategies to occasionally undergo spontaneous mutagenesis and thus to contribute to biological evolution. Biological evolution does not depend on errors and accidents; the genetic setup of living organisms enables them to autonomously undergo evolution at the level of their population. In their natural habitats living organisms mostly cohabit with other kinds of living organisms. This allows them to mutually profit from each other by symbiosis, i.e. by helping each other. A good example are the microbiomes, the cohabitation of microorganisms with eukaryotic plants and animals, including humans. We now realize that our own genome is not solely responsible for our life activities, some of which are carried out with the help of cohabiting microorganisms. Furthermore, long-term cohabitation occasionally offers the chance to transfer one or a few genes horizontally between the different kinds of organisms. Horizontal gene transfer has been identified to represent an important evolution strategy, in addition to spontaneous intragenomic genetic variation. Therefore, we do not only have a common past with other kinds of organisms, we also have a common future with cohabiting organisms.

The products of several natural barriers against viral infection and too frequent horizontal gene transfer, in particular between microorganisms, have now become used for so-called gene editing, i.e. altering particular nucleotide sequences in the genome. In principle, this can also help to repair undesirable mutants, but the application of this method should strictly respect ethical considerations.

Scientific investigations have recently revealed various sources of erroneous malformation, in particular during embryonic development. The sources include: the lack of certain essential micronutrients (hidden hunger) or viral infection, such as by the Zika virus. We strongly hope that scientists find appropriate means to prevent these kinds of unhealthy developments. Resilience has in particular become a topic in neurobiology by natural means to prevent wrong developments. Please see Appendix 1 for a more detailed summary of this Session.

Our Academy is aware of a number of largely unpredicted harmful impacts of certain human activities. An example that has been discussed again is climate change, which is based on several sources, which are rooted both in geophysical events and in human activities. The latter are of serious concern if the expanding needs of the developing world for energy, especially electric power, are supplied by the burning of fossil fuels. A further example of harmful human activity, as revealed by recent studies, is the increase in ocean contamination due to plastic pollution.

Concern was also expressed regarding the ongoing practice of organ trafficking and transplant tourism. On the other hand, our Academy was pleased to receive information on recent progress in the fight against cancer.

As previously mentioned, the increased use of renewable energy sources can significantly contribute to preventing negative environmental impacts of human activities. These sources are within reach and deserve to be promoted.

Through contributions made to the special session devoted to *Food and Nutrition and the Role of Biotechnology in Agriculture*, it has become apparent that scientific means are available and should be utilized to improve the nutritional quality of daily diets of all human beings. Appropriate scientific education, coupled with a wide respect of ethical rules, can be expected to contribute to this development. The Academicians believe that encouragement by the Church would be beneficial and would contribute to preventing malnutrition and its negative impacts on human health, from the early embryo up to old age. Relevant biotechnological innovations are known not to cause unpredictable danger. Rather, they largely follow the laws of Nature for biological evolution. Therefore, responsibly applied biotechnological methodologies can importantly contribute to improving human health and eventually also preserve the rich diversity of our habitats and their inhabitants. In the Appendix 2 you will find a summary of this Session.

Appendix 1. Biomedicine

In the area of biomedicine it was discussed how the microbial world has cohabitated since the early stages of life. Horizontal transfer of large numbers of genes and genomes are still today being exchanged. Thus, transgenic organisms are an integral part of the microbial world which surrounds and lives inside the human body.

Potent new genome editing techniques have become available very recently. This technology known as CRISPR/Cas9 has an awesome power to direct changes to specific regions of the DNA using simply a 20-nucleotide mRNA and a bacterial nuclease called Cas9. This system, normally used by many bacteria to acquire immunity to viruses, has an enormous potential to modify crops and animals but the modification of the human germ line presents enormous dangers and is to be strictly avoided. However, CRISPR/Cas9 gene editing has potential for the treatment of human diseases in somatic tissues, such as cancer-producing DNA translocations that generate novel sequences and viruses such as HIV that integrate in subsets of immune cells.

It was also discussed how high-throughput genome sequencing is now making it possible to identify many loss-of-function mutations that affect only one copy of a gene yet can produce human malformations. These *de novo* mutations are absent from both parents and originated in their germ cells. Unexpectedly, the human genome contains hundreds, possibly thousands of genes that can cause birth defects. Congenital disease is also caused by the Zika virus epidemic that is now sweeping the world and especially Latin America, leaving in its aftermath many children with microcephaly and epilepsy. The sanctity of the life of these malformed children will have to be defended vigorously from a global secular culture that openly defends euthanasia, as was presciently foreseen by St. John Paul in the 1995 encyclical *Evangelium Vitae*, paragraph 3.

Appendix 2. Food and Nutrition

1. Pope Francis emphasized food security and sustainability in addressing the Pontifical Academy of Science (PAS) on 28 November 2016. Poverty and extreme inequality must be overcome, because it is poor women, men, and children who suffer most from hunger and undernutrition. About 800 million people are hungry and about 2 billion suffer from so called "hidden hunger", i.e. they are deficient in micronutrients. This problem must be addressed with much more urgency, especially the Vitamin A deficiencies among children that can lead to blindness, and often death during the childhood.
2. We at PAS emphasize that science can play a key role in ending hunger and undernutrition, as indicated by the earlier PAS session on *Bread and Brain* (2013), which addressed some related themes, including the adverse long-term neurological consequences of undernutrition.
3. We took note of the food needs of present and future generations and concluded that at least approximately 50% more food production is needed by 2050. We also emphasized that not just more, but more healthy food, that is accessible and affordable by low-income people is needed. Stronger food, nutrition, and agriculture science systems that serve the poor are needed.

4. We considered various options to overcome so called "hidden hunger" (i.e. the micronutrient deficiencies of Iron, Vitamin A, Zinc, etc.) and their devastating short- and long-term health effects. Sustainable approaches are plant breeding innovations that get more micro-nutrients into the crops grown year after year, referred to as biofortification. The undernourished have no time to loose, therefore such promising approaches need to be scaled up faster and combined with other approaches to achieve fast nutrition progress, including industrial food fortification, medical supplementation, and promotion of nutrition-sensitive local agriculture and horticulture.
5. We also noted that consumption habits of the wealthy need changing. We observe, with concern, that much food is lost in production and after harvest, as well as wasted in consumption. While we need better practices to cut losses and a new respect for food to cut waste, even when waste and losses are reduced, a lot more food production is needed in the coming five decades. While redistribution of wealth between rich and poor is called for, redistribution of food is not a solution to the hunger and malnutrition problems.
6. Food and nutrition security must be in harmony with nature and the environment. We build our deliberations on the earlier PAS/PASS session on *Sustainable Humanity – Sustainable Nature* (2014). All food must be produced more sustainably with respect to soils, water, biodiversity and climate sensitivity. We benefitted from new insights about prevention of soil degradation, no-till cultivation, and precision farming.
7. We noted that genetically modified crops have in fact brought significant income benefits to the poor already, but not yet direct consumption benefits, because of regulatory barriers. We took note of promising crop-biological innovations including with genetic modifications that use less resources, produce less greenhouse gases, are higher yielding, and which have more micronutrient contents. These innovative crops should be tested at scale, and released quickly if they hold promise.
8. We are aware of widespread reservations against genetically modified crops, which is partly fostered by scary, unfounded information. The fact that GMOs are connected to some large corporations may also be fostering rejection of GMOs. As it had already been requested in 1975 at the Asilomar Conference, solid risk assessments should accompany any new technology introductions. We call for a focus on product characteristics and proven benefits. Information to the public is needed, for instance that gene transfers among organisms is part of natural evolu-

tion including the plants.At the same time research is needed to better understand the root causes of attitude and fear formation, including food fears and biotechnologies.

9. We received comprehensive information about new molecular-biological methods (including gene-edited, and genetically modified crops) that offer opportunities to facilitate increased income and better nutrition of the poor. As our Academy noted before, in 2010, solid and transparent testing including for health and environmental aspects, of context specific applications of GMOs is required, as for any crop innovations. Regulations must be science- and evidence-based and not dominated by advocating special interest groups. It is time to revisit and appropriately use biological innovations in agriculture in support of nutrition of the poor.

APPENDIX

La Technoscience et ses défis

Jean-Michel Maldamé, O.P.

Les philosophes ont mis la technique en procès. Nul n'ignore la célèbre phrase où une des figures les plus éminentes de la philosophie du XX^{e} siècle, Martin Heidegger, porte un jugement péremptoire: «La science ne pense pas»[1] – pour lui, science et technique sont intiment liées comme le dit clairement la notion de «technoscience». Le caractère excessif du propos a suscité tant de commentaires qu'il ne s'agit pas ici de la prendre comme référence faisant autorité, mais tout simplement ici dans le but d'éveiller notre attention sur le fait que si la technique est au centre de bien des débats de société, elle est aussi au cœur des questions anthropologiques et théologiques. Parler de technique ne consiste pas à promouvoir une bonne gestion de capacités d'action et de transformation, mais bien à poser la question du sens de la vie humaine et se situer le rapport entre l'intelligence, la volonté et le pouvoir de tout être humain sur lui et sur la société qui le porte. Pour cette raison notre propos quittera l'immédiate actualité pour ouvrir des perspectives plus larges et plus profondes.

1. Mise en perspective

La question de la technique a été posée dans sa radicalité au seuil du XX^{e} siècle lors de la première guerre mondiale. Une œuvre emblématique

[1] «La raison de cette situation est que la science ne pense pas. Elle ne pense pas, parce que sa démarche et ses moyens auxiliaires sont tels qu'elle ne peut pas penser – nous voulons dire penser à la manière des penseurs. Que la science ne puisse pas *penser*, il ne faut voir là aucun défaut, mais bien un avantage. Seul cet avantage assure à la science un accès possible à des domaines d'objets répondant à ses modes de recherches ; seul il lui permet de s'y établir. La science ne pense pas : cette proposition choque notre conception habituelle de la science. Laissons-lui son caractère choquant, alors même qu'une autre la suit, à savoir que, comme toute action ou abstention de l'homme, la science ne peut rien sans la pensée. Seulement, la relation de la science à la pensée n'est authentique et féconde que lorsque l'abîme qui sépare les sciences et la pensée est devenu visible et lorsqu'il apparaît qu'on ne peut jeter sur lui aucun pont. Il n'y a pas de pont qui conduise des sciences vers la pensée, il n'y a que le saut. Là où il nous porte, ce n'est pas seulement l'autre bord que nous trouvons, mais une région entièrement nouvelle. Ce qu'elle nous ouvre ne peut jamais être démontré, si démontrer veut dire : dériver des propositions concernant une question donnée, à partir de prémisses convenables, par des chaînes de raisonnements». Heidegger, *Essais et conférences,* « Que veut dire penser ? », Paris, Gallimard, 1953.

de cette prise de conscience s'exprime dans la littérature européenne avec l'œuvre de Robert Musil, *L'Homme sans qualité* (*Der Mann ohne Eigenschaften*), qui fait le procès de la modernité où la rationalité technique se limite à l'étude de rapport de forces et par là-même ignore les vraies causes de la difficulté de vivre et la source des malheurs qui ont vu s'effondrer un art de vivre. Le déroulement de la guerre mondiale atteste la puissance aveugle de l'industrie (emblématiquement «le charbon et l'acier») et l'usage de moyens techniques (chimie et électronique). Le philosophe Karl Kraus dans *La troisième Nuit de Walpurgis* (*Die Dritte Walpurgis Nacht*) reprend sur un mode dramatique ce procès dans sa dénonciation de la montée des totalitarismes appuyée sur la puissance donnée par la technoscience, dans la «contemporanéité de l'électronique et de la décomposition radioactive». Ces textes ont le mérite de lier la technique aux mythes ou aux rêves qui l'accompagnent avec les sources noires de la mythologie. Ces deux auteurs européens, témoins et prophètes, ont dénoncé la technique comme moyen mis au service de la volonté de domination et l'aveuglement de la philosophie du progrès. Bien d'autres ensuite ont repris ces thèmes. La question s'est déplacée.

Dans la deuxième partie du XX^e^ siècle, la question a pris un élan nouveau avec la revendication écologique. La critique a trouvé son plus brillant analyste et promoteur avec le philosophe Hans Jonas. Celui-ci ne se contentait pas de dénonces effets, mais il cherchait à déterminer la source du malheur qui afflige l'humanité (*Das Prinzip Verantwortung. Versuch einer Ethik für die technologische Zivilisation*, 1979). Sa vision de la nature était fondée sur une philosophie de la vie, articulée à une métaphysique qui n'ignore pas les fondements bibliques de la modernité et de la crise de civilisation qui menace l'avenir humain sur la planète Terre. Au début du XX^e^ siècle, la question se pose de manière plus précise dans le projet nord-américain de construire un «homme nouveau», un homme qui surmonte les limites actuelles des conditions de vie et propose une nouvelle religion hédoniste.

Cette rapide évocation philosophique avait pour but de sortir de l'idée simpliste selon laquelle la technique serait un ensemble de moyens que les sciences permettent de mettre à l'usage des humains. Et corrélativement, de ne pas tomber dans le simplisme qui consiste à faire quelques rappels des exigences morales fondées sur l'humanisme ou sur la notion de «personne», comme sujet de droits et de devoirs. À l'encontre de cette réduction, tout en maintenant la distinction entre science et technique, je pense éclairant de montrer que la technique ne se réduit pas à un ensemble ou un réseau de moyens d'action, mais qu'elle participe de la pensée et donc de la grandeur de l'humain.

2. L'animal humain, être de culture

La question de la spécificité humaine est posée aujourd'hui par les sciences du vivant, puisque la théorie de l'évolution donne à voir l'émergence de l'humanité selon les embranchements du grand arbre des vivants. L'humain est plus animal et les animaux plus humains que ne l'imaginait la tradition humaniste. Dans ce contexte, il est bon de revenir aux sources et de citer Aristote qui a écrit le premier grand traité sur les vivants. Dans les ouvrages *Histoire des animaux* (*Perì tá zõa historíai*), *Les Parties des animaux* (*Perì zõõn moríôn*) et le *Traité de l'âme* (*Peri psychè*), il situait l'humanité dans le monde des vivants et il relevait un trait spécifique de l'humanité. Il constatait qu'à sa naissance l'être humain était le plus démuni de tous les animaux; en effet, laissé à lui-même l'enfant n'a pas les moyens d'assurer sa survie. Sa nudité, son manque de moyen pour se nourrir et se défendre… font de lui le plus vulnérable des êtres vivants. Il notait que, par contre, s'il était dépourvu de griffe, de sabot, de pelage, de mobilité et autres moyens de survivre dans le combat de la vie, un être humain avait une main. Celle-ci était «l'outil de tous les outils» et elle lui donnait les capacités de l'emporter sur les autres animaux. La main était l'organe de l'intelligence et la source de la maîtrise de l'humanité sur les autres vivants. Aujourd'hui encore l'outil devenu technique et partie prenante de la technoscience est le signe de la grandeur de l'homme et la source d'une redoutable efficacité – thème de notre interrogation.

Plus encore! La main, «outil de tous les outils», était pour Aristote l'inscription de l'intelligence dans l'ordre du faire et de l'action de transformation et surtout de qualification dans une compétence. C'est là le point clef de ce que nous appelons aujourd'hui l'émergence de l'«*homo sapiens*». L'usage de la main est explicité dans la culture classique par le terme de «métier» qui dit la sagesse et l'art issus de l'expérience, forme de sagesse pratique. Par son action, un être humain individuellement considéré ou l'humanité dans une vision globale agissent dans le monde où il leur est donné de vivre; l'humanité transforme ce qui lui est donné dans la nature. Plus encore, il se transforme lui-même et il accède à la culture. Il est heureux que dans les langues européennes le terme ait gardé le sens premier né de la révolution néolithique où les ressources alimentaires agricoles ou animales aient accompagné la naissance des villes et des communications entre les humains par le commerce et la collaboration qui ont dessiné la toile que nous qualifions de mondialisation (*globalisation*).

La démarche d'Aristote est habitée par une ambition métaphysique: dire la spécificité humaine en relevant ce qui fait partie de son identité ou encore de sa nature. Cette perspective donne à la remarque sur l'usage de l'outil une dimension ontologique. L'outil permet de dire ce qui fait l'homme humain. Que ce soit l'outil des temps anciens, comme le marteau ou la roue ou les outils les plus significatifs de la modernité, comme l'ordinateur devenu familier ou les grandes réalisations industrielles comme les centrales nucléaires… Il est clair que la technique ne se réduit pas à la production d'objet, mais dit la qualité de l'être humain, comme celui qui a le pouvoir de devenir lui-même en faisant de qui lui permet d'assurer sa survie. La technique n'est pas seulement la production d'un objet mis à la disposition d'un individu ou d'une communauté, elle est ce qui permet à un être humain en devenir de se réaliser en devenant ce qu'il est appelé à être.

La référence à Aristote peut sembler archaïque, en ramenant la réflexion au monde tel qu'il fut au temps où Archimède faisait quelques pas sur la route qui a mené à la modernité. Une perspective analogue se trouve dans les travaux de Hannah Arendt. Celle-ci a entrepris d'écrire une synthèse philosophique présentant l'anthropologie philosophique; elle a renoué avec les traditions universitaires en considérant ce qui relève de l'intelligence et de la volonté (*La Vie de l'esprit*), mais aussi de l'action (*Condition de l'homme moderne* et *La Crise de la culture*). Ces deux dernières études explicitent la nature de la technique; Hannah Arendt ne considère pas seulement l'objet, mais l'engagement de l'être humain dans son action, par laquelle il se réalise. L'art est une autocréation de soi.

Il est éclairant d'entrer dans une perspective psychologique, en développant une image. L'objet technique est en position d'extériorité, mais ce n'est pas un objet de la nature, car il ne peut être pensé sans référence à celui ou ceux qui l'ont produit. L'image du miroir correspond à cette situation. Le miroir renvoie à celui qui se regarde une représentation de ce qu'il est. Non pas tout ce qu'il est en lui-même, mais par cette image de soi une évaluation de l'humain. La psychologie l'enseigne. Dans l'image que leur donne le miroir, les adolescents scrutent l'énigme de leur identité, au moment où ils déchirent les liens du tissu familial pour devenir eux-mêmes face à un avenir inconnu. En psychanalyse, la notion de miroir évoque aussi un stade antérieur de la constitution du sujet humain: dans la petite enfance où il s'agit d'une toute première découverte. Mais la métaphore du miroir vaut pour tous les âges de la vie. La métaphore vaut pour tout objet technique qui ne peut jamais être réduit à son utilité. Si grande que soit l'utilité, elle est toujours une quête de l'identité humaine. L'objet technique est une réalisation de soi qui est à la fois une expression de son être et un pas fait en avant pour devenir autre. La projection de soi dans l'objet est au cœur de l'exigence de vivre sa pleine humanité.

Certes, la technique est une réalisation qui relève de l'utile, mais elle est bien davantage. Elle est un lieu de construction et d'affirmation de soi, dans un contexte qui s'appelle une culture. L'image familière du miroir permet de porter un jugement plus équilibré sur la technique et d'éviter de la présenter comme l'horizon ultime de la vie humaine aussi bien que de l'accuser comme source d'aliénation.

3. La technologie: machines et progrès industriel

Les critiques de la technique sont un «fil rouge» pour porter un jugement sur la civilisation et ses exigences de modernité. Il est éclairant d'en retracer les perspectives. Elles sont éclairées par un glissement dans le vocabulaire. Au XIXe siècle, le mot «technologie» désignait à l'origine le savoir concernant la technique (le *logos* de la *teknè*) et les tentatives pour mettre en forme les savoir-faire artisanaux. Au XX^{e} siècle, le terme «technologie» désigne l'ensemble des procédés industriels et leurs produits à une époque donnée. Il aussi est employé comme synonyme de «technique moderne». L'histoire des conflits sociaux en montre la complexité.

Les premières manifestations hostiles contre la modernité sont venues des ouvriers et des artisans face aux premières machines au XVIIe siècle (1675 à Londres) et au XVIIIe (1769 Lancashire, 1780 Manchester, etc.). En effet, les artisans ont constaté qu'un métier à tisser faisait en quelques heures ce que faisait une dizaine de tisserands pendant une semaine. L'installation des machines les réduisait au chômage et donc leur enlevait leur gagne-pain. Plus encore les machines demandaient à être servies et le travail devenait un asservissement. «Nous ne sommes pas faits pour nous démener entre deux roues comme des écureuils en cage», disait un de ces tisserands en révolte. La querelle du machinisme a été alors ouverte. Elle opposait deux visions du monde. On peut les systématiser emblématiquement: d'une part, celle de Jean-Jacques Rousseau qui valorisait la notion de «nature» et, d'autre part, celle qui prenait pour emblème la notion de progrès. Selon cette philosophie du progrès, l'usage de la machine était l'instrument d'une réalisation de l'idéal humain d'être «maître et possesseur de la nature». Elle reposait sur la reconnaissance de la valeur de l'usage de la raison. Dans le débat qui s'est instauré la référence à la rigueur de la démarche scientifique a été un argument décisif pour justifier la modernisation industrielle, au nom de la rationalisation du travail et de la division du travail. On utilisait le raisonnement suivant: la machine est construite selon les acquis de la science et de ce fait elle évite les incertitudes et les aléas de la nature. La maîtrise de la nature est encore aujourd'hui présente dans l'association de la science et de la technique comme source de progrès – la technoscience désigne encore pour beaucoup la voie de l'avenir en permettant de répondre aux besoins vitaux de l'humanité.

Précisons encore que si les faits historiques et culturels évoqués relèvent du passé pour les habitants des pays développés, il ne faudrait pas oublier qu'ils ont été au cœur des grands projets de conquête du monde par les pays de l'Ouest européen puis d'Amérique du Nord. L'ouverture à la modernité a été liée au recours aux techniques industrielles, par exemple au Japon au XIXe siècle, mais aussi au XX^{e} siècle en Chine… On peut relire en ce sens l'histoire de la colonisation, des luttes sociales (en Russie) et les grands conflits mondiaux évoqués plus haut à propos des guerres du XX^{e} siècle et encore aujourd'hui dans le choc des cultures traditionnelles et de la technologie non seulement électronique, mais d'abord agricole.

4. Le Système technicien

L'idéologie du progrès, qui a justifié l'industrialisation, s'est renouvelée au XX^{e} siècle. Elle a rencontré un obstacle majeur déjà évoqué: la conduite de la guerre a montré comment l'armement produit par les grands systèmes industriels multipliait l'horreur de la guerre. Non seulement les soldats mourraient par centaines de milliers sur le champ de bataille, mais les populations civiles étaient plus que jamais victimes des bombardements. L'usage et le développement de l'arme nucléaire a porté ceci à son comble. Une nouvelle période de la critique de la technoscience est alors ouverte. Elle est fondée sur la critique de l'idée de progrès. Plus encore que l'accroissement de la puissance, ce qui retient l'attention c'est la constitution d'un «système».

Parmi les auteurs sont emblématiques de cette critique caractéristique du XX^{e} siècle (Ivan Illich, Lewis Mumford…) nous retiendrons Jacques Ellul, auteur de deux ouvrages à nos yeux fondamentaux. Le premier est un éveil aux questions de civilisation, *La Technique ou l'enjeu du siècle*, le second une vision globale, *Le Système technicien*. Pour J. Ellul, un système, c'est «un ensemble d'éléments en relation les uns avec les autres de telle façon que toute évolution de l'un provoque une évolution de l'ensemble, toute modification de l'ensemble se répercutant sur chaque élément». La technique ne se réduit pas au machinisme, elle inclut également les méthodes d'organisation de la vie sociale, du travail comme de la Cité. J. Ellul prend le mot «technique» dans le sens le plus large possible; pour lui, «partout où il y a recherche et application de moyens nouveaux en fonction du critère d'efficacité, on peut dire qu'il y a technique» (technique d'apprentissage de la lecture, techniques sportives et bien sûr toutes les techniques mécaniques). Il note que la technicisation envahit tout le champ de l'activité humaine. Il discerne dans ce mouvement qui s'universalise, une autonomie et une spécificité qui lui permet de défendre l'idée d'une unité «sous-jacente» de l'ensemble sous le concept de «système» qu'il situe dans son contexte économico-politique. Les objets et des moyens qui composent le «système technicien» constituent comme un «milieu» qui isole l'homme de ses éléments naturels. Il n'y a plus d'autres liens entre l'homme et la nature que ceux qu'autorise l'appréhension technique aux dépens des autres liens complexes et fragiles que l'homme avait su patiemment tisser, comme les liens poétiques, symboliques et magiques, qui sont amenés à disparaître. Cette interdépendance s'intensifie avec l'informatique. De ce fait, la société actuelle n'est pas la «société humaniste» fortifiée par des moyens techniques supplémentaires, elle est autre. Pour le montrer, il est éclairant que relever quatre caractères du «système technicien» : autonomie, unité, universalité et totalisation.

D'abord, l'autonomie se voit vis-à-vis des pouvoirs politiques, mais aussi vis-à-vis de l'économie. Cette autonomie se développe aussi vis-à-vis des impératifs moraux puisque la technique ne supporte l'immixtion du jugement moral. Dans un monde technique devenu autonome, les travaux philosophiques ou éthiques n'ont d'intérêt que privativement et ne doivent jamais interférer sur leurs travaux. J. Ellul voit poindre corrélativement une éthique technicienne qui promeut ses propres valeurs (précision, exactitude, sérieux, réalisme et par-dessus vertu au travail). En troisième lieu, l'unicité est l'expression concrète du système. Avec la technique moderne ce qui est nouveau c'est que chaque découverte peut s'appliquer, et le fait effectivement, dans le meilleur délai à un nombre considérable de domaines. Les moyens informatiques le permettent non seulement dans le développement de ce qui est lié à la communication, mais en tout domaine: en matière médicale, financière, spatiale et autres domaines présentés comme les fleurons du progrès. En deuxième lieu, l'universalité s'entend, puisque la technique empiétant progressivement sur tout l'environnement et une universalité géographique, aucun pays ne pouvant rester au dehors. Enfin, la totalisation vient par le fait que pour la technique, il n'y a aucune opération impossible ou interdite.

L'analyse critique de Jacques Ellul repose sur une certaine conception d'être humain qui, selon la tradition protestante, dont il est un porte-parole éminent, valorise la liberté individuelle et le primat de la conscience. Sa démarche est fort différente de la valorisation de la nature et sa sacralisation, sentiment qui domine les courants écologiques nord-américains. Sa démarche nous semble importante, car elle montre bien que la question n'est pas limitée à un domaine d'activité, mais concerne le projet de construction de soi que porte l'être humain. Nous pensons qu'il est loisible de conclure que le projet de la technoscience est une projection que les êtres humains font d'eux-mêmes. Si leur intention et leur esprit est habité par des exigences de pureté et de bonté, la technoscience sera source de paix et de développement équilibré. Si l'esprit est habité par le seul souci du profit, de la possession dans l'oubli des conséquences pour les plus fragiles, la technoscience sera source de catastrophes et de déclin.

5. Science et technique

L'image que la civilisation actuelle se donne repose sur un certain nombre de valeurs ou d'idéaux. Parmi eux se trouve la valorisation de la science. Sur ce point, il est utile de revenir à l'analyse philosophique qui articule la science et la technique, comme dans la célèbre citation de Heidegger. Celui-ci amalgame la science et la technique. Ce n'est pas sans fondement, mais cette manière de faire porte un danger, celui que nous avons vu dans le paragraphe sur la technologie: ce n'est pas parce que les objets techniques sont le fruit d'une application des sciences qu'ils participent à sa bonté et à sa pureté. Il faut marquer une différence qui ne soit pas de l'ordre d'une hiérarchisation, car cette manière d'ordonner marque toujours un certain mépris. Pour sortir de ce mépris, il faut percevoir le champ où les termes de science, technique et philosophie s'enracinent.

Heidegger se justifie d'avoir dit que «la science ne pense pas» en relevant que la science moderne est seulement de l'ordre du calcul.[2] La science

[2] «Cette phrase: "La science ne pense pas", qui a fait tant de bruit lorsque je l'ai prononcée dans le cadre d'une conférence à Fribourg, signifie: la science ne se meut pas dans la dimension de la philosophie; mais, sans le savoir, elle a trait à cette dimension. Par exemple, la métaphysique se meut dans le domaine de l'espace, du temps et du mouvement. Mais *ce qu'est* le mouvement, l'espace, le temps – la science –, en tant que science, ne peut pas en décider. La science ne pense donc pas, elle ne peut pas penser – en ce sens – avec ses méthodes. Je ne peux pas dire, par exemple, physiquement, avec les méthodes de la physique, *ce qu'est* la physique. *Ce qu'est* la physique, je ne puis le penser que sur le mode philosophique. La phrase: «la science ne pense pas» n'est pas un

repose sur des concepts premiers qui sont l'apanage de la philosophie. Ainsi le scientifique reçoit du philosophe des concepts (par exemple, ceux d'espace et de temps ou même de vitesse); il met en forme opératoire ce que ces concepts portent en eux-mêmes et ainsi il peut calculer et par là même prédire le cours du mouvement dans l'espace et le temps. La différence entre la physique et la philosophie est radicale. Cette vision positiviste de la science convient pour la technique qui n'est que l'application de ce que la science établit de manière abstraite. Cette conception n'est pas la nôtre. S'il est vrai que la science et la philosophie ne se confondent pas et si la conceptualisation philosophique est à la fois plus large et plus profonde que celle de la science, les processus de construction, d'explicitation et de vérification des énoncés scientifiques impliquent une philosophie qui leur est immanente. Il en va de même pour la technique qui est le fruit d'un engagement de l'intelligence humaine dans la transformation du des ressources disponibles dans la nature et dans l'humanité.

Ayant bien vu que toute séparation radicale entre science, technique et philosophie sont impossibles, il faut voir que leurs différences sont réelles. Le philosophe est engagé dans une quête qui porte sur l'être en tant qu'être au croisement de l'essence et de l'existence, du savoir et du pouvoir, de l'amour et de la pensée. Le scientifique, au sens moderne du terme, c'est-à-dire un savoir lié à l'usage du langage mathématique, entend expliquer la raison des phénomènes observables et quantifiables, formalisée dans un langage technique et ainsi trouver les lois qui régissent les phénomènes de la nature. Il est toujours habité par la question du pourquoi; il entend y répondre en usant rigoureusement de l'observation, de l'expérimentation et de la formalisation de lois universelles qui transcendent les singularités advenant dans l'espace et le temps. Elle n'est pas hors d'une singularité, puisqu'elle utilise un langage précis et même univoque. La technique a un autre propos; elle entend optimiser le rapport entre les moyens et les exigences de la vie humaine, individuelle ou sociale. Elle est donc orientée vers le concret, et l'action utile à l'humanité. La différence est irréductible – ce qui ne veut nullement dire qu'il n'y ait pas d'interaction. La science est source de progrès techniques, mais elle dépend elle aussi de la technique. Ainsi les travaux sur le célèbre boson de Higgs sont liés à la capacité technique d'accéder à des énergies où les collisions de particules sont

reproche, c'est une simple constatation quant à la structure interne de la science; c'est le propre de son essence que, d'une part, elle dépend de ce que la philosophie pense mais que, d'autre part, elle-même oublie et néglige ce qui exige là d'être pensé».

observables et mesurables. Science et technique participent d'une visée philosophique, tant pratique que théorique.

Dans cette perspective, qui écarte tout mépris à l'égard des trois attitudes humaines ici relevées, il apparaît donc que l'interaction entre ces trois champs de l'activité spécifiquement humaine est fondamentale; elle existe non seulement dans le souci éthique actuel qui vise à contrôler les applications techniques au monde humain, mais dans leur fondement même. Nous le voyons clairement dans un domaine aujourd'hui en plein essor: l'intelligence artificielle et au cœur des utopies nouvelles.

6. Intelligence artificielle

La notion d'intelligence artificielle (I.A.) provient des travaux des pionniers de la cybernétique au milieu du XX^e^ siècle. Aujourd'hui, l'expression désigne ce qui est au cœur des grands projets de développement. L'expression dit une vaste ambition: celle d'une réalisation technique d'une compétence spécifiquement humaine, dite par le terme «intelligence», fruit de l'industrie humaine et dite pour cela «artificielle». Cette ambition est le fruit de la rencontre de plusieurs savoirs: logique, linguistique, informatique, mathématiques et investissement stratégique et industriel – et cela grâce à des ordinateurs mis en réseau. L'ordinateur est une machine capable de conduire des calculs mathématiques. Plus encore! La machine peut faire du calcul propositionnel.

L'I.A. repose sur des «systèmes experts». Ceux-ci fonctionnent selon une logique formelle qui prend en compte les propositions (comme la logique ancienne) mais aussi les prédicats où la notion mathématique de «variable» est importante car elle permet la quantification. Les progrès de l'I.A. sont ceux des logiques dites «non classiques», les «logiques modales» qui sortent du cadre binaire de la logique classique (entre vrai et faux, il y a le probable ou l'incertain). Cela permet de rejoindre le langage naturel, mais aussi de mettre en œuvre une logistique. Ce terme désigne l'ensemble des opérations et des moyens relatifs à un service, une entreprise, comportant des éléments d'information, de conditionnement, de transport, d'approvisionnement. C'est une science de l'action qui repose sur la communication. C'est ainsi que l'I.A. repose sur l'échange et la communication de l'information. Il nous faut réfléchir sur ce qu'est l'information pour élucider les questions posées par l'I.A.

Le terme «information», qui a donné le mot «informatique», signifie dans le langage commun trois éléments mis ensemble dans l'I.A. En premier lieu, l'action de donner connaissance de faits, ou plus généralement de rechercher les éléments d'un événement ou d'une réflexion; en ce sens le verbe «s'informer» signifie dans la forme passive recevoir et dans la forme active chercher à savoir. En deuxième lieu, l'information est un renseignement sur quelque chose ou sur quelqu'un, ou une nouvelle ou un message, portés à la connaissance de quelqu'un. Ce sens habituel préside à la notion d'information utilisée dans les medias pour désigner une transmission de connaissance ou une communication. Il y a plus. En troisième lieu, dans l'acte de transmission et de réception du message il y a une intention. C'est ainsi qu'une information concernant un fait précis et singulier n'a pas grand sens quand elle est isolée, car elle prend sens dans l'ensemble des «informations» qui le concerne et le met en rapport avec des faits semblables ou liés de manière non immédiatement perçue. Ces trois fonctions de communication ont une autre dimension, dite par l'origine du terme «information».

L'intention de l'information est triple. D'abord, que celui qui est informé – celui qui reçoit le message – acquiert une connaissance qui lui sera utile. La pancarte «danger de mort», «interdiction d'entrer sur le chantier» est là pour le protéger en prévenant une imprudence… Ensuite, l'intention de celui qui envoie le message est de partager son savoir et cela dans des buts spécifiques – commerciaux dans la publicité, politique dans les journaux, moraux dans l'éducation ou scientifiques dans l'enseignement, etc. Enfin, l'établissement d'un lien nouveau entre celui qui envoie le message et celui qui le reçoit. C'est la raison pour laquelle on emploie le mot «forme» présent dans les termes «informer» ou «information». Nous y voyons la trace philosophique du langage de la philosophie de la nature de la tradition aristotélicienne. Pour elle, un être se définit par sa forme, le principe qui préside à la l'organisation de la matière, dont il est constitué. L'information est un acte qui constitue un être dans ce qui le fait tel ou tel. L'information est toujours une «transformation», ce n'est pas seulement un transfert. Pour nous, la science dite informatique n'est pas seulement une technique de transfert de données, c'est une construction qui a lieu dans trois domaines. D'abord, la constitution d'un récepteur. Ensuite, l'acte de préparer et d'élaborer ce qui sera transmis. Enfin, la constitution d'un réseau de relations et donc une communion sociale. Ainsi l'informatique, science de l'information, est porteuse d'une vision d'ensemble dans un projet culturel. Si elle est une prouesse technique, dans la composition de ses éléments constitutifs et de leur organisation, elle est un acte formateur d'un mode d'être humain spécifique. Elle donne une forme particulière à ses objets: l'écriture, le calcul, les liens et aussi les associations de mots, d'idées et d'images. La forme donnée est précise; il est clair que ce ne n'est pas la seule et unique manière de communiquer en humanité. En raison de cette limitation, sans mépris aucun, il est nécessaire de relever qu'il existe d'autres chemins où l'humain s'accomplit.

La situation tout à la fois éminente et singulière de l'Intelligence Artificielle se voit clairement dans une de ses activités, celle qui est exprimée par le terme de «mémoire». Ce terme se réfère à une énigme de la vie: comment rendre présent ce qui n'est plus? Les débats philosophiques relèvent que la mémoire n'est en rien un donné inerte, mais un acte complexe. Edward Casey (*Remembering. A Phenomenological Study*) distingue entre trois modes: *Reminding, Reminiscing* et *Recognizing. Reminding* correspond aux indicateurs qui protègent contre l'oubli. A l'intérieur de l'esprit par l'apprentissage comme à l'extérieur comme les notes, reçus, photos ou archives. *Reminiscing* désigne un effort plus soutenu pour faire revenir à l'esprit ce qui fut. *Recognizing*, reconnaissance, enfin associe le souvenir présent et l'impression première visée comme autre. Ainsi la mémoire est ouverte sur du neuf. La technologie en donne les moyens, mais elle reste figée dans une seule dimension, celle de la conservation. La dimension de créativité de l'esprit humain ne lui appartient pas.

7. Être au monde

Les moyens d'action donnés par la technoscience ont permis de grandes réalisations. La capacité de transformation des conditions vie a été multipliée de manière considérable. L'effet n'a pas été seulement de multiplier la production et la diversité des éléments utiles à la vie. La conséquence a été de permettre la croissance quasi exponentielle de la population humaine, mais aussi de transformer le milieu de vie humaine. Les niveaux atteints par la croissance démographique comme les modifications de l'environnement ont été de plus élevés et de ce fait, un événement nouveau et advenu: l'irréversibilité des transformations opérées et la crainte pour l'avenir.

Pour juger de ces transformations, une distinction est utile. Deux termes nord-américains font image et s'opposent de manière claire: *mining* et *farming*. Le premier évoque l'exploitation minière, le second l'activité agricole traditionnelle. Dans la première activité, l'industrie humaine puise dans les ressources disponibles; elle arrache les éléments désirés (minerai, énergie fossile…) et cela sans retour possible. Ce qui est ensuite transformé ne peut revenir à l'état initial; les énergies utilisées ne se reconstitueront pas. Le temps est ici irréversible. Par contre dans le travail agricole mené «en bon père de famille», selon l'expression habituelle, le fermier agit avec le souci de la récolte prochaine; il travaille la terre, amende les sols ou sélectionne les semences ou les plants de manière à produire mieux et plus aux saisons suivantes. Ces deux manières donnent des modèles pour juger de la conduite de l'activité humaine. Elles montrent que selon l'intention et l'attention à ses productions, l'être humain développe la technoscience pour le meilleur ou pour le pire. Il y a eu sur ce point une aggravation du champ de la responsabilité.

Dans les premiers temps de l'industrialisation, l'action se portait sur la «nature», terme général pour dire l'environnement humain et les possibilités données pour la transformation des ressources nécessaires à la vie. Les débats sur la crise écologique ont été riches, ils montrent bien comment l'humanité entend «être au monde», soit comme possesseur dans un esprit de domination ou d'exploitation soit comme gérant dans un esprit de développement et de respect. Aujourd'hui la technologie permet davantage et la responsabilité engagée est plus grave. Cela est dû au fait que les possibilités d'action humaines touchent le plus intime des vivants. Les travaux sur le génome, sur les processus de reproduction et sur les éléments qui changent les relations et les communications relèvent d'une autre instance. Ils ne concernent pas un monde en vis-à-vis de l'homme, mais l'identité humaine elle-même. Cet aspect est au cœur du débat actuel concernant la «convergence NBCI» qui présente une utopie et un programme d'action (Roco Mihail C. & Bainbridge William Sims, *Converging Technologies for Improving Human Performance. Nanotechnology, Biotechnology, Information Technology and Cognitive Science*). Le projet nord-américain a suscité de nombreuses réactions et même une réponse quasi officielle de l'Union Européenne (Nordmann Alfred, *Converging technologies. Shaping the future of European Societies*). L'enjeu du débat instauré par l'utopie qui résulte de la convergence des technologies est de définir la motivation immanente aux projets humains et à ce que l'on entend faire des moyens technologiques dont on dispose. Le développement de la technologie pose donc la question du sens de la vie humaine. Nous n'avons pas ici à en juger du point de vue moral, mais à situer et à articuler la complexité humaine dans ses motivations.

Le projet des humains de maîtriser leur destin est très ancien. Il est de toujours, car tout vivant est mu par l'appétit de vivre – de cette tension vers l'avant, la volonté consciente n'est qu'une partie émergée. Sur ce point, il est éclairant de rappeler la distinction classique faite en psychanalyse entre le besoin et le désir. Un être humain est confronté aux nécessités de poser les actes fondamentaux de la vie. Il a besoin de manger, de boire, de dormir, de se vêtir, de se bâtir une demeure, de vivre en famille ou dans une société… L'expérience montre que quand ces besoins sont assouvis, il y a en lui un mouvement qui ne cesse pas. Non seulement avoir plus et mieux, mais passer outre pour réaliser une aspiration plus grande. Celle-ci porte la trace de l'infini, un infini que rien ne saurait combler. Tout être humain est un être de désir, ouvert vers un infini. Jamais il ne cessera de désirer, d'être en mouvement.

Cette tension vers ce qui est toujours devant comme un horizon qui s'élargit au fur et à mesure que l'on avance ou monte sur le chemin, est la caractéristique de l'être humain. En premier lieu dans la relation humaine où l'autre n'est pas seulement celui qui vient combler un besoin, mais celui qui appelle à un mouvement qui ne peut se contenter de posséder car alors il se dénature ou se perverti. Ces remarques élémentaires sont pertinentes pour situer les débats sur la technologie.

Le vouloir humain ne se rassasie pas d'une réalisation particulière. Nous entrons ainsi dans une perspective plus radicale, tant par son ampleur que par sa profondeur. Nous avons situé la technologie ou le monde des objets techniques dans une perspective dynamique avec l'image du miroir. Un être humain y cherche son identité et il découvre ce qu'il est. L'objectivation que lui donne l'image qui obtient de lui-même lui permet de se réaliser. C'est alors que se pose la question radicale qui est au cœur de toute culture. Que signifie «se réaliser» pour un être humain? Est-ce devenir ce qu'il veut être? Ce vouloir est-il éclairé par une claire vision? Si un idéal ou un projet est proposé à la conscience peut-on en juger? Peut-on l'apprécier sans en connaître la source?

C'est alors que se posent des questions les plus radicales, parce qu'elles concernent l'origine et la fin.

Sur ce point, il est éclairant de citer un des philosophes les plus en vue dans la critique des fondements de la technique moderne, Hans Jonas (*Essais philosophiques: du credo ancien à l'homme technologique*, 1974). Contre le réductionnisme de la méthode scientifique, il en appelle à la parole fondatrice de son identité juive, telle qu'elle apparait dans les premières pages de la Bible et qui, pour cette raison, vaut plus largement, de manière universelle en métaphysique ou dans les religions. Il relève que la notion de création enseigne «la vénération envers la nature et envers l'homme». Il relève que pour ce qui est de la nature une nécessité. Pour lui, il y a «quelque chose d'absolu, le respect pour la manifestation de la vie sur cette terre». Il relève aussi que l'affirmation que l'être humain (*Adam*) a été créé «à l'image de Dieu», est au principe d'un projet de vie, privilégiant l'éducation, le respect et la mise à distance de toute volonté prométhéenne de produire une humanité défigurée.

Du point de vue catholique, il importe de reconnaître que l'Évangile apporte une dimension spécifique. La tradition chrétienne a des convictions fortes sur l'origine et sur la finalité de la vie humaine. Dire que l'être humain est créé par Dieu d'une manière spéciale et dire que l'horizon de la vie n'est pas l'anéantissement signé par la mort, mais la «résurrection de la chair» (de quelque façon qu'on se la représente), change la manière de vivre. Elle rend vigilant face aux réalisations historiques qui montrent comment l'enfermement dans la seule rationalité est source d'aliénation et de stérilité – comme le relèvent des figures de la pensée catholique, comme Bernanos hier ou Rémi Brague aujourd'hui.

Nous n'avons pas à juger ici de ces propositions, mais nous pouvons par contre, en restant au plan de la philosophie, reconnaître que la technologie humaine renforce la conviction que l'humanité doit assumer la responsabilité de modifier la vie et le devenir de l'humanité.

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Pour finir, voici quelques convictions personnelles, fruits de notre analyse.

1°- Nous prenons au sérieux la révolution technologique et son impact sur la culture en commençant par la formation de l'esprit humain. Emblématiquement aujourd'hui le développement de l'I.A. qui n'est pas sans influence sur la conception de l'humanité. Cela dans un cercle où se renforce l'idée d'intelligence préalable à sa fondation.

2°- Il n'est pas possible de réduire les apports de la technologie à la technicité des machines et des systèmes qui seraient «neutres». Ils concernent le sens de la vie individuelle ou communautaire. Le développement technologique est une explicitation des options premières. Faut-il attendre les sanctions venues avec les catastrophes?

3°- Le développement technologique en cours marque-t-il un saut qualitatif? Oui! Ce saut peut-il être considéré comme un «progrès»? Le terme «progrès» est riche de l'énergie humaine qu'il mobilise; il est aussi grevé par les idéologies dont il a servi d'emblème. Il nous faut préciser notre pensée: l'expérience montre que ce que l'on appelle «progrès» ne change pas la condition humaine; le développement dit «progrès» produit un déplacement. Il en va alors comme de la vision; l'expérience commune montre qu'elle a toujours la même amplitude; quand quelqu'un se tourne, son regard se porte sur un champ nouveau; il peut voir ce qu'il ne voyait pas avant, mais il n'a plus accès à des éléments qui étaient vus, puisque désormais hors de son champ de vision. Ainsi l'expérience de la modernité montre que si les champs d'action sont différents, la condition humaine ne change pas fondamentalement. Ainsi tout en reconnaissant que les technologies gagnent en puissance et en finesse, nous constatons que l'humanité est la même, existentiellement mais pas essentiellement.

4°- Il est nécessaire de distinguer entre science et sagesse. La sagesse est une vue pacifiée et une approche intériorisée de la réalité. La science est une pénétration à l'intime du réel qui permet la connaissance et la maîtrise technologique, mais elle reste toujours face à une irréductible frontière née de la nécessaire spécialisation.

5°- Si certains disent avoir peur de la technologie moderne et développent une apologie du retour à l'état préscientifique ou préindustriel, ce n'est pas notre perspective. Les technologies modernes sont une belle ressource où s'accomplit une certaine dimension de l'intelligence humaine - même si la technologie, comme toute activité humaine, a sa part d'ombre.

6°- L'histoire de la pensée donne plusieurs figures de démesure. Nous aimons citer le mythe du Golem. Selon le mythe, un très savant rabbin avait construit un serviteur qui accomplit parfaitement toutes les tâches nécessaires à sa vie matérielle. Il attestait le pouvoir créateur de l'homme, qui respectait la Loi de Dieu. Mais un jour arriva où le Golem détruisit ce qu'il était censé contribuer à réaliser. Ce récit dénonce la perversion de la sagesse.

7°- La théologie chrétienne radicalise les points précédents en montrant bien que l'homme est image de Dieu et donc responsable de son achèvement. Comme le disent les textes bibliques fondateurs, une tentation est toujours présente: adorer l'œuvre de ses mains et donc d'entrer dans le cercle vicieux de l'aliénation ou de l'idéologie qui ne vit plus la liberté des enfants de Dieu.

Bibliographie

Arendt Hannah, *The Human Condition*, Chicago, University of Chicago Press, 1958; *La Condition de l'homme moderne* Paris, Calmann-Lévy, 1961.

Arendt Hannah, *The Life of the Mind*, t. 1: *Thinking*, t. 2: *Willing*, New York, Harcourt; Brace Jovanovitch, 1978, *La Vie de l'esprit*, Paris, PUF, 1983.

Arendt Hannah, *La Crise de la culture*, Paris, Gallimard, 1972.

Bernanos Georges, *La France contre les robots*, Paris, Robert Laffont, 1945.

Besnier Jean-Michel, *L'Homme simplifié. Le syndrome de la touche étoile*, Paris, Fayard, 2012.

Blay Michel, *Dieu, la nature et l'homme.* L'originalité de l'Occident, Paris, Armand Colin, 2013.

Blay Michel, *Penser ou cliquer?*, Paris, CNRS-éditions, 2016.

Casey Edward, *Remembering. A Phenomenological Study*, Indiana University Press, 1987.

Dehaene Stanislas, «Apprentissage et sciences cognitives», *Cités*, 63, 2015, p. 81-97.

Ellul Jaques, *Le Système technicien*, Paris, Calmann-Lévy, 1977 et Le Cherche-Midi, 2012.

Friedmann Georges, *La Puissance et la Sagesse*, Paris, Gallimard, 1970.

Hadot Pierre, *Le Voile d'Isis. Essai sur l'histoire de l'idée de Nature*, Paris, Gallimard, 2004.

Heidegger Martin, *Essais et conférences*, trad. fr., Paris, Gallimard, 1953.

Hottois Gilbert, *Penser la logique.* Une introduction technique, théorique et philosophique à la logique formelle, Bruxelles, De Boeck Université, 1989.

Jarrige François, *Techno-critiques. Du refus des machines à la contestation des technosciences*, Paris, La Découverte, 2016.

Jonas Hans, *The Phenomenon of Life. Toward a Philosophical Biology*, Harper & Row, New York, 1968.

Jonas Hans, *Das Prinzip Verantwortung. Versuch einer Ethik für die technologische Zivilisation*, Insel Verlag, Frankfurt-am-Main, 1979 (*Le Principe responsabilité*, Paris, 1990).

Jonas *Hans, Philosophical Essays, From Ancient Creed to Technological Man*, Midway reprint, University of Chicago Press, 2013.

Kraus Karl, *Die Dritte Walpurgisnacht,* Erschienen, 1952.

Le Moigne Jean-Louis, *Intelligence des mécanismes, mécanismes de l'intelligence*, Paris, Fayard, 1986.

Musil Robert, *Der Mann ohne Eigenschaften, 1. & 2. Teil, 1930, 3. Teil, 1933.*

Lenoble Robert, *Histoire de l'idée de nature*, Paris, Albin Michel, 1969.

Manier Bénédicte, *Un million de révolutions tranquilles: travail, environnement, santé, argent, habitat: comment les citoyens transforment le monde*, Paris, édit. Les Liens qui libèrent, 2012.

Nordmann Alfred, *Converging technologies. Shaping the future of European Societies,* A Report from the High Level Expert Group on Foresighting the New Technological Wave, Luxembourg, Official Office of the European Communities, 2004.

Roco Mihail C. & Bainbridge William Sims, *Converging Technologies for Improving Human performance. Nanotechnology, Biotechnology, Information Technology and Cognitive Science,* Dordrecht, Boston, London, Kluwer Academic Publishers, 2003.

Rosa Hartmut, *Aliénation et Accélération. Vers une théorie critique de la modernité tardive*, Paris, La Découverte, 2012.

Séris Jean-Pierre, *La Technique*, Paris, PUF, 1994.

Wagner Peter, *Progress. A reconstruction*, trad. fr. *Sauver le progrès*. Comment rendre l'avenir à nouveau désirable, Paris, La Découverte, 2016.