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THE FACTS OF LIFE

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Introduction

The last fifty years have witnessed major advances in our understanding of the nature and history of life on Earth. The implications of these advances have yet to be incorporated into current philosophical and religious world-views, which are still largely pervaded by animist concepts that belong to an earlier age. The main points at issue are briefly reviewed in the present paper. A more comprehensive treatment of the subject is to be found in a recent book (de Duve, 2002).

FACTS AND THEORIES

In considering present-day knowledge, it is important to distinguish between facts and theories. The former may be viewed as incontrovertibly established, whereas the latter, even though they may be supported by all available evidence, remain open to discussion and possible dissent. In the summary that follows, I shall try to make this distinction, although the limit beyond which a theory becomes a fact is not always easy to define.

1. *Life Is One*

All living organisms, including bacteria, protists, plants, fungi, animals, and humans, descend from a single ancestral form, known as the *last universal common ancestor*, or *LUCA*. The kinship among all forms of life, long supported by their many structural and functional similarities, has now been proven beyond doubt by the sequence similarities among genes that perform the same function in different organisms. Hundreds of such cases are known.

Not only do the similarities prove descent from a single ancestral sequence. Even the differences are revealing, as they tend to be all the more numerous the greater the evolutionary distance separating the organisms that own the genes, thereby allowing the construction of molecular phylogenies.

2. *Life Is a Natural Process*

Here, again, the proofs are overwhelming. Thanks to recent advances in biochemistry, cell biology, and molecular biology, we have reached a stage where we may confidently state that we *understand* life. Admittedly, vast areas, in fields such as embryological development or the functioning of the brain, continue to pose challenging problems to research. Many details remain to be filled in. But the basic processes that support life, those that are common to all living organisms – metabolic pathways, biosynthetic mechanisms, energy transformations, genetic information transfers – can be explained in terms of molecular structures and reactions. This is so true that we can now manipulate life almost at will.

An important lesson to be derived from this newly-gained knowledge is that the age-old view of life as 'animated matter', which is still implicitly prevalent in much of current thought and discourse, is plainly wrong. There is no such thing as a nonmaterial 'vital force' or 'vital spirit' that somehow moves the molecular components of living organisms to behave the way they do. *Vitalism is no longer tenable.* Life is a normal manifestation of matter, entirely explainable in terms of physics and chemistry. Although solidly established scientifically, this fact has yet to become accepted knowledge by much of the general public.

3. *Life Is Ancient*

Alleged vestiges of bacterial life – including fossil traces of microorganisms, mineralized remains of large, complex, bacterial colonies, called stromatolites, and carbon deposits containing an excess of the light ^{12}C carbon isotope over the heavier ^{13}C, taken to be a signature of biological activity – have been discovered in a number of ancient geological sites, some as old as 3.5, or even 3.85 billion years. Doubts have recently been expressed about the authenticity of some of this evidence, putting into question the date of first appearance of life on Earth. This controversy is far from settled, but other, unquestioned signs of past life exist that go back well beyond 3.0 billion years. Furthermore, the organisms that have left such traces appear distinctly more advanced than the LUCA is likely to have been; and the LUCA itself must have been preceded by a string of more primitive organisms. Finally, the probability of finding preserved vestiges of past life in ancient rocks becomes increasingly small as the age of the rocks increases, and, with it, the likely destruction of these vestiges by metamorphic and other changes. For all these reasons, it seems probable that life is actually more ancient than the available evidence would seem to indicate. Its age could well exceed 3.5 billion years by an appreciable margin.

This age is to be compared with that of the Earth, which was born about 4.55 billion years ago. At that time, some 10 billion years after the Big Bang, the Earth condensed, together with the other planets of the solar system, within a disk of dust and gas whirling around a glowing core that was to become our Sun. Our nascent planet, battered by planetesimals, comets, and meteorites and convulsed by volcanic upheavals, remained unable to harbor life for at least 500 million years. Thus, life may have appeared on Earth almost as soon as the planet became physically able to bear it.

This possibility has led some workers to suggest that there would not have been enough time for life to arise locally, so it did not start on Earth but was brought to it from some extraterrestrial site by a comet, a meteorite, or some other means of transportation (even including a spaceship sent out by some distant civilization!). As will be seen, this argument rests on an erroneous estimate of the time needed for the emergence of life. Another piece of evidence put forward in favor of an extraterrestrial origin of life has been the discovery, which will be referred to later, that organic material is widespread in the Universe. However, it is now generally accepted that this material is of nonbiological origin. It thus seems reasonable to suppose that life originated on Earth. An advantage of this hypothesis for the purpose of research is that available geochemical data on the state of the early Earth help to narrow down the problem by defining the physical-chemical setting in which life may have originated.

The fact remains that an extraterrestrial origin of life cannot be discounted on the strength of present evidence. Neither can the possibility be ruled out that life originated in more than one site, for example on Mars or even on celestial bodies outside the solar system. As we shall see below, such eventualities are now generating considerable interest.

4. Life Arose Naturally

This is a theory, not a fact, as there is no direct proof that life did, or even can, arise naturally. But there is plenty of circumstantial evidence supporting such a possibility. Particularly convincing is the fact, stated above, that life is a natural process, entirely explainable without calling on the intervention of some 'vital spirit'. That such a process may itself arise naturally clearly appears as the most likely hypothesis. From the point of view of research, it is the only acceptable hypothesis. Scientific investigation requires the presupposition that its object be explainable.

A powerful argument in support of a natural origin of life has been provided in recent years by the spectroscopic exploration of outer space, the study of comets with the help of instruments borne by spacecraft, and, especially, the analysis of meteorites by means of all the techniques of modern chemistry. These investigations have revealed the astonishing fact that amino acids and other biological constituents form spontaneously in large amounts throughout the Universe. Thus, at least the building blocks of life are *natural products of cosmic chemistry*. The alternative hypothesis, sometimes formulated by the defenders of an extraterrestrial origin of Earth life, that living organisms are responsible for the synthesis of the detected compounds, is not considered tenable.

In the last forty years, numerous attempts have been made to reproduce in the laboratory some steps of the origin of life. Sparked by the historic experiments of Stanley Miller (1953), much of this effort has been directed towards the formation of small, organic building blocks of life. The finding, just mentioned, that such materials readily arise under natural conditions has lessened interest in this line of research. The main focus, nowadays, has shifted to the reactions whereby such building blocks could have assembled into more complex molecules, especially RNA, which, according to all that is known, probably played a crucial role in the early development of life.

So far, these efforts have met with limited success. But this is no reason for giving up. What may be needed is a change of approach, calling more on biochemistry than on organic chemistry in the design of experiments. Living cells show us at least one pathway whereby building blocks are combined into complex biological constituents by natural reactions. As I have pointed out elsewhere, there are good reasons to believe that the early chemistry that first produced life already prefigured some of the key processes by which life constructs itself in present-day organisms (de Duve, 2002).

The theory of a natural origin of life is far from being unanimously accepted. It is, of course, rejected and even violently combated by fundamentalists and creationists, who put greater store on a literal reading of the biblical account of Genesis than on scientific evidence and who, on this basis, negate not only the natural origin of life but even the existence of a

LUCA and the occurrence of biological evolution. Many less committed laypersons, some even highly educated, share the same attitude, not so much for religious reasons than because of the largely unconscious, ingrained vitalism that still pervades all that has to do with life. To this point must be added the powerful prejudice against 'spontaneous generation', popularized by what may well be the most celebrated experiment by Pasteur, who, incidentally, was a confirmed vitalist. This prejudice rests on a misapprehension. What Pasteur showed, and nobody will deny, is that microbes cannot arise spontaneously overnight in a sterile broth protected from aerial contamination. What origin-of-life research attempts to elucidate is a process of gradual 'complexification' that must have taken a considerable amount of time to give rise to the first primitive microbes.

In recent years, opposition to the notion of a natural origin of life has been voiced by a very small but vocal minority of scientifically trained persons who, while subscribing to the notion of a LUCA appearing *de novo* on Earth and evolving into present-day living organisms, claim that these phenomena could not possibly have taken place by purely natural processes, but required the intervention of some nonmaterial guiding entity that forced the raw materials of life to interact so as to produce the first living cells and also, as will be mentioned later, directed the further course of evolution (Behe, 1996; Dembski, 1998; Denton, 1998). Known under the name of 'intelligent design', this theory, which is close to vitalism, has been magnified much beyond its merits because of its alleged philosophical and theological implications. I shall come back to it when discussing evolution. Let me simply state now that serious flaws have been detected in the scientific arguments brought forward in its support.

The question of the origin of life deserves one additional comment: it is a *chemical* problem. What needs to be unravelled is the pathway, itself made of chemical reactions, between two kinds of chemistry: cosmic chemistry and biological chemistry. This fact entails two implications. First, the process must, for kinetic reasons, have been relatively *fast*. What is meant by this term is difficult to evaluate. My own estimate of the requisite time is anything from centuries to millennia, perhaps tens of millennia or even more, but certainly not tens or hundreds of millions of years, as was once believed by those who, for this reason, defended an extraterrestrial origin of life (see above). The fragility of many of the intermediates involved in the process precludes such very slow reactions.

A second consequence of the chemical nature of the processes responsible for the origin of life is that these processes must have been highly *deterministic* and reproducible. Like all chemical processes, they depended only on the physical-chemical conditions that prevailed where they happened, and they were therefore *bound to occur* under those conditions. This opinion is not shared by all scientists. On the contrary, the most widely held theory, for a long time, was that life arose as the outcome of highly improbable, chance events, so improbable that they are most unlikely to take place anywhere else, any time, and could very well not have happened on Earth either, were it not for the fantastic stroke of luck that made them possible. I shall discuss this theory later, in relation to the possible existence of extraterrestrial life. Let me just point out that its defenders unwittingly – and unwillingly – provided support to those who claim that life could not have arisen without the help of some special agency, or even an act of God. From a fantastic stroke of luck to a miracle, the mental step is short.

5. *The Theory of Evolution Is More than a Hypothesis*

In those words, Pope John-Paul II, addressing the Pontifical Academy of Sciences in a solemn session, on 22 October 1996, expressed the acceptance of biological evolution by the Church. Considering the implications of this statement, the evidence that convinced the Pontiff must be truly decisive. And so it is. Actually, the Pope's statement was overly cautious. Evolution is not a theory; it is a fact, implicit in the common descent of all living organisms and established with the same degree of certainty.

Thanks to the information provided by fossils and complemented by molecular phylogenies, we have a rough idea of the timing and manner in which evolution has proceeded. A schematic outline of its main steps is shown in Table 1. Bacteria were the sole representatives of life on Earth during more than one billion years. The first eukaryotes emerged around 2.2 billion years ago, probably as the outcome of a long evolutionary history of which no fossil trace has yet been found; they remained unicellular for more than another billion years. It is only after life had completed some three-fourths of its history on Earth that primitive multicellular plants, fungi, and animals first appeared, slowly giving rise to more complex forms. The animals, in particular, went through more than 99-hundredths of their own history before producing the last common ancestor of humans and their closest relatives, the chimpanzees. In the final hominization stage, *Homo sapiens sapiens*, our nearest forebear, appeared only about 200,000 years ago. In absolute terms, this is a huge expanse of time: 100 times the duration that has elapsed since the birth of Christ. In relative

Table 1. THE HISTORY OF LIFE

MILLION YEARS (approximate)	EVENT
-15,000	Big Bang
- 4,550	Birth of Solar System (Earth)
- 4,000	Earth Habitable
- 3,500	First Bacteria
- 2,200	First Eukaryotic Protists
- 1,000	First Plants and Fungi
- 600	First Invertebrates
- 500	First Fish
- 400	First Amphibians
- 350	First Reptiles
- 225	First Mammals
- 70	First Primates
- 6	Last Common Chimpanzee-Human Ancestor
- 0.2	Homo Sapiens
- 0.030	Cro-Magnon
- 0.002	Birth of Christ
0	Present
+ ???	End of Humankind ?
+ ???	? ? ? ? ?
+ 5,000	Explosion of Sun (Earth Uninhabitable)

terms, however, it is little more than one twenty-thousandth of the age of life on Earth, or the equivalent of the last half-hour in one entire year.

Two directions may be distinguished in the course of evolution. One, which I call *vertical*, proceeds in the direction of increasing *complexity*: from bacteria to eukaryotes; from unicellular protists to pluricellular plants, fungi, and animals; and, in each of these groups, from simple to increasingly complex organisms, with – at this point in time – the human species as summit in the animal line. At each level of complexity, *horizontal* evolution has produced a wide *diversity* of organisms, making up the rich array of species that compose each class.

6. *Natural Selection Is the Main Mechanism of Biological Evolution*

Modern molecular biology has provided powerful support, as well as a large amount of additional information, to the theory of natural selection first proposed by Charles Darwin. Many details of the theory are still being discussed, sometimes heatedly, among experts. But its main elements are largely undisputed.

To start with, there is *heredity*, the phenomenon whereby properties are transmitted from generation to generation. Known as an empirical observation by Darwin and his contemporaries, later quantified by Mendel in a manner that implied the existence of units of inheritance, or genes, this phenomenon is now understood in detailed molecular terms thanks to the discoveries of molecular biology.

Next, there is *variability*, which creates breaks in genetic continuity and allows the start of new evolutionary lines. The phenomena responsible for the breaks, called mutations, can now likewise be described in molecular terms and related to a number of physical, chemical, or biological causes acting in a manner that is well understood.

Finally, *natural selection* screens the mutant products of genetic variability according to their ability to survive and produce progeny under prevailing environmental conditions. In addition to being a logical necessity, natural selection has been seen in action, at least on the short term of human observation, in a number of instances. Resistance to toxic chemicals is a prominent example that has been documented in bacteria, protists, plants, and animals.

The most important information provided by modern biology is that the genetic changes responsible for evolutionary branchings are strictly *accidental* events, totally *devoid of intentionality*. Mosquitoes do not become resistant to DDT *in order to* escape from the toxic effect of the pesticide. Those rare individuals that *happen to be* resistant to DDT survive and proliferate in the presence of the chemical. All that is known of the mechanisms involved imposes this interpretation.

In simple terms, this understanding implies that each of the many forks that have, over almost four billion years, delineated the course of evolution, is the product of a *chance* genetic change that happened, again by *chance*, to take place in an environment conducive to the survival and proliferation of the mutant form. These facts are recognized by a vast majority of life scientists, even though there may be disagreements on certain details or side issues, such as the importance of neutral mutations, genetic drift, and the mechanisms of speciation, to cite only a few. Exceptions are the few defenders of 'intelligent design', already mentioned above, who claim that certain key steps in evolution, for example, the transformation of reptiles into birds, could not possibly have taken place by a strictly Darwinian mechanism and that some hidden agency must have guided the process according to a pre-set plan. The following quotation illustrates this viewpoint: 'It is hard not to be inclined to see an element of foresight in the evolution of the avian lung, which may well have developed in primitive birds before its full utility could be exploited' (Denton, 1998, p. 362). Note the terms 'foresight' and 'before', which are characteristic of this kind of thinking.

Intelligent design is but a new word for a theory known as 'finalism' (from Aristotle's final causes). Favored by a number of biologists of the nineteenth and early twentieth centuries, finalism slowly yielded to the convincing arguments of Darwinism and has now been abandoned, together with vitalism, in response to the advances of modern biology. Its present revival in the face of all the evidence against it is not scientifically justified, as has been abundantly shown (see: Miller, 1999; de Duve, 2002).

The theory of intelligent design would hardly be worth mentioning in a serious scientific context were it not for its amalgamation – consciously advocated by its supporters – with so-called 'spiritualist' philosophies, in opposition to the crass 'materialism' allegedly professed by scientists. Thus, intelligent design has become a rallying banner, enthusiastically hailed in some religious circles, for a number of philosophers, theologians, and creationists of one ilk or another, who emphasize that 'science does not explain everything', a statement, incidentally, few scientists would take issue with. Such confusion of some vaguely conceived animism with religion is unfortunate. It hardly helps the cause it is supposed to serve, which can only be weakened by identification with a dubious scientific theory. Among the many thinkers who have expressed themselves on this point, special mention deserves to be made of the late French philosopher Jean Guitton (1991) and the American biochemist Kenneth Miller (1999), both practicing Catholics.

Our understanding of the underlying mechanisms gives chance a central role in each of the many branchings that trace the course of evolution. According to most experts, this realization enforces the conclusion that evolution, including, in particular, the advent of humankind, has depended on such a large accumulation of fortuitous coincidences that its repetition anywhere, any time, cannot possibly be envisaged. In the words of Ernst Mayr, one of the most distinguished and respected representatives of the field, 'an evolutionist is impressed by the incredible improbability of intelligent life ever to have evolved' (Mayr, 1988). As will be seen, many have gone one step further and used this view as an argument for denying any significance to humankind.

Although seemingly inescapable, the conclusion reached by such scientists is not flawless (de Duve, 2002). Contrary to the intuitive perception sometimes evoked by the notion of randomness, chance does not necessarily exclude inevitability. All depends on the quantitative ratio between the number of *opportunities* provided for a given event to happen and the *probability* of the event's happening. Given enough opportunities, an event may be almost bound to take place – within limits of physical feasibility, of course – however improbable it may be.

This notion is highly relevant to evolution, which usually involves large numbers of individuals – millions, if not billions or more – competing for available resources, generation after generation, for up to millions of years. What this means in practice is that, in many cases, the genetic variants offered to natural selection cover the field of possibilities so extensively as to make the outcome almost predictable, given the environmental conditions that prevail. Witness in support of this affirmation the many cases of drug resistance already referred to – an almost unavoidable consequence, so it seems, of introducing a new drug into the environment – as well as many other remarkable instances of adaptation – mimicry is a good example – that have been marshalled in support of finalism in the past, and still are cited by the defenders of intelligent design today.

Allowing for a number of exceptions, the conclusion suggested by these considerations is that, in many cases, mutations are not the limiting factor of evolution, leaving the main role to the environment and its vagaries. It is important here to distinguish between horizontal and vertical evolution (see above). In horizontal evolution, which involves variations of the same body plan, environmental conditions play the leading role. Mimicry illustrates this point. Absent green leaves, no insect with leaf-like shape and color would be selected.

Things are different in vertical evolution, in which significant changes in body plan – from reptile to bird, for example – take place by way of intermediates that must all be viable and capable of successfully proliferating under prevailing conditions. The inner and outer constraints that narrow down the course of such pathways are stringent, and the role of chance is correspondingly reduced. In a number of instances, there are only one or very few courses for evolution to take, and the environment does no more than passively determine whether a course will or will not be taken.

Such considerations are relevant to the widely accepted view that so many chance events have been involved in evolution as to make it virtually impossible that a similar unfolding could ever happen elsewhere. This, no doubt, is true of many details of horizontal evolution, although, even here, one is impressed by many remarkable instances of convergent evolution (Conway Morris, 1998; Nevo, 1999). But when it comes to the main directions of vertical evolution, including the advent of humankind, the constraints may be such that, given appropriate conditions, similar directions may well be followed time and again, without the necessary assistance of a guiding agency.

7. *Earth Life Has up to Five Billion Years Left for Further Evolution*

Cosmologists tell us that the Sun will have exhausted its stores of energy in about 5.0 billion years, at which time it will expand into a red giant, enveloping the Earth in a fiery embrace and making the planet unfit for life. Other planetary catastrophes may extinguish life earlier, but probably not before 1.5 billion years, according to most estimates. Even this lower value is a truly enormous time, more than twice the evolutionary history of animals, 250 times the leap from chimpanzee to human, 200,000 times humankind's written historical record, some 20 million human lifetimes! The higher estimate allows life a future longer than the whole of its past.

What will happen in such huge expanses of time is obviously impossible to predict, or even to visualize. But some surmises based on past history are permissible. First, it is likely that life, which has survived so many planetary cataclysms, will persist in one form or another until the Earth becomes utterly uninhabitable. Next, it is safe to say that life will not remain at a standstill. Evolution, including our own, will continue, eventually leading to new forms that could be as different from present-day organisms as are sequoias from seaweeds or human beings from sponges. In particular, as will be mentioned below, if vertical evolution keeps proceeding in the direction of increasing complexity, beings with mental faculties much more highly developed than our own may well appear one day.

This, however, is only one scenario, inspired by past history. A much more dismal future could await life in general and humankind in particular. Evolution could regress, the biosphere could become poorer, humankind could disappear. The crucial factor here is that natural selection, although still operating, will no longer be solely in charge. Humankind now holds its future and that of life on Earth in its own hands. I shall come back to this point at the end of my essay.

8. *Life, Even Intelligence, May Be Widespread in the Cosmos*

This statement expresses a mere possibility, so far unsupported by any concrete evidence and long considered most unlikely by the majority. Opinions have changed. Many scientists now consider the existence of extraterrestrial life likely enough to justify great efforts and expenditures. A new discipline, named astrobiology, has formed around this topic. Explorations of Mars and other parts of the solar system aimed at uncovering signs of life have been carried out and more are planned. The search has extended to nearby stars, creating considerable excitement with the discovery of the first extra-solar planets. Even extraterrestrial intelligence is actively looked for by attempting to detect signals from any distant civilizations that may exist.

Although these efforts have not met with any success so far, the possibilities that inspire them appear plausible, perhaps even probable. In the preceding pages, I have defended the notion that life was bound to arise under the physical-chemical conditions that prevailed at the site of its birth. The main reason for this contention is that the processes involved were essentially chemical in nature and, therefore, highly deterministic and dependent only on existing conditions. A corollary of this view is that, if the same conditions obtain elsewhere in the Universe, life would likewise arise at that site and would have the same basic chemical properties that characterize life on Earth. With some 30 billion Sun-like stars in our Galaxy alone and about 100 billion galaxies in the Universe, the likelihood of the existence of other planets sufficiently similar to the

Earth to be capable of giving rise to life would seem to be very high. Most astronomers agree on this point.

Whereas the existence of extraterrestrial life is now considered likely by a majority of scientists, opinions are much less sanguine concerning the likelihood that life may evolve to produce intelligent, humanlike beings. As mentioned above, many evolutionists see this eventuality as most unlikely and view humankind as the unique product of an extremely improbable concatenation of chance events. It may be significant, in this respect, that the participants in the SETI project (Search for ExtraTerrestrial Intelligence) are mostly astronomers.

The biologists' skepticism may not be justified. As I hope to have shown, the well-established role of chance in evolution is restricted by two factors that are not always sufficiently appreciated. One is the richness of the mutational field presented to natural selection, with the result that the outcome under given environmental conditions often ends up limited to a small number of (optimized) possibilities. The other factor to be taken into account is the stringency of the inner and outer constraints that tend to channel evolution in the vertical direction whenever the opportunity arises. According to this line of reasoning, the emergence of humankind – and also, incidentally, that of beings of higher intelligence in the future – turns out to be a much less improbable event than is often maintained. That extraterrestrial life may evolve in a similar direction is also, by the same token, a realistic possibility.

The Human Condition

Our philosophies and religions, our social systems, our laws, our cultures, our civilizations, even our sciences and our cosmologies, are all traditionally centered on humanity. Terms such as human rights, human dignity, human freedom have acquired quasi-mystical status, under the unifying notion of *humanism*, which, from its literary origin in the Renaissance, has become the rallying concept of all human-centered reflections and activities. How could it be otherwise in a world where 'species-ism', the allegiance to one's species, has been deeply etched in by natural selection?

It has required modern science to shake the foundations of anthropocentrism. After relegating our abode to a speck of cosmic dust orbiting around one in one hundred billion stars, in one among one hundred billion galaxies, science has now shown that we are one out of millions of twigs that have branched from the tree of life on Earth over a span of some four billion years. This realization is only beginning to be felt by people outside scientific circles. Scientists disagree on its significance. In this essay, I focus on three aspects of humankind that I believe particularly deserve to be taken into account: transience, meaning, and responsibility.

1. *The Transience of Humankind*

This is probably the most revealing lesson of modern biology; it is also the most disturbing. For most of the existence of life on Earth, we were not around. We will most likely cease to be around long before life disappears from our planet. We are no more than a transient manifestation of life, a stage in its long evolution towards diversity and complexity, almost certainly *not the ultimate outcome* of this process.

Most likely, the road to humankind consisted of small increments – notably in brain size – without any sharp discontinuity. The perceived break between humans and their closest primate relatives is the artificial consequence of the lack of surviving missing links. The slow evolution of stone cultures over more than two million years illustrates this course in impressive fashion. It is only after the human species had acquired its characteristic modern features that cultural evolution started picking up, thanks perhaps to the acquisition of language, and went on proceeding at an ever increasing pace, up to the vertiginous rate we see today.

According to anthropologists, there has been no significant increase in the size of the human brain – and presumably in its associated mental capacities – during the last 50,000 years. An interesting question is whether such an increase will, or can, occur in the future. Whether it will occur may depend to some extent on our own interventions, as I shall mention below. Whether it can occur will only be known if it happens, but the possibility can hardly be ruled out on the strength of present knowledge.

It is illuminating, in this connection, to look from an historical perspective at the development of the human brain and the associated mental abilities. As already emphasized (Table 1), the last hominization steps have taken a remarkably short time relative to the preceding history of life on Earth and to its likely future. This fleeting period has been witness to an amazingly rapid increase in brain size, which, in just a few million years, has grown to three times the size it had taken one hundred times as long to reach before that. The cerebral cortex, the seat of consciousness, has expanded even more – more than four times – during that period. As illustrated by selected examples in Table 2, there has been a parallel expansion

Table 2. THE GROWTH OF MENTAL POWER

CEREBRAL CORTEX (cm^2)	PERFORMANCE ABILITY
500	Fishing Termites with Stick
1 000	Chipping Stone Tools
2 200	Sending Man to the Moon Nuclear Power, Supercomputers Genetic Engineering ----- Big Bang, Quarks, Relativity Natural Selection, Double Helix ----- Lascaux, Sistine Ceilings, Guernica Angkor Vat, Parthenon, Chartres Well-tempered Clavier, Ninth Symphony ----- Divina Commedia, Hamlet ----- Holy Bible, Discours de la Méthode
4 000	? ? ?

of mental performance, from the crude manifestations of purposeful intelligence shown by chimpanzees to the highest achievements of human culture. What if the cerebral cortex should expand even further? This question is unanswerable with our present brains. Beings better endowed mentally are as impossible for us to imagine as would have been Moses or Einstein, or even the humblest of illiterate humans, for Lucy, the young australopithecene female that roamed the Afar region, in East Africa, some 3.0 million years ago. What our minds do allow, however, is our raising the possibility and considering its implications.

Such a development need not necessarily take place in the human line. Humankind could disappear, and some other evolutionary line could take over and eventually lead to beings mentally superior to humans. There is certainly enough time for such a happening. All this is speculation, of course. I mention it simply to underline the fact that there is no objective reason to assume that humankind occupies some sort of evolutionary summit beyond which evolution in the direction of further complexity is impossible.

Another possibility that now deserves seriously to be taken into consideration is that other intelligent beings, some perhaps even mentally superior to us, may exist elsewhere in the Universe. Because of the immensities of cosmic times and distances, such beings may never come to be known to Earth humans. But their existence appears sufficiently plausible, if not probable, to be included as a possibility in any world-view.

What all this amounts to is that *humanism*, while continuing to rule our societies within the framework of human concerns, *must be dissociated from anthropocentrism*, the philosophical view that gives humankind a privileged position within some sort of cosmic blueprint designed around and for it. Whereas the former deserves to be maintained for obvious pragmatic reasons, the latter needs to be abandoned or, at least, amended by our philosophies and religions if they aim at universality. Admittedly, this necessary reappraisal will not be easy.

2. *The Meaning of Humankind*

In the eyes of many biologists, the reappraisal called for by science is drastic. It entails the recognition that there is no meaning whatsoever to humankind. We are no more than the accidental product of an enormous number of highly improbable chance events that could very well never have taken place, whether on Earth or anywhere else, and, therefore, are totally devoid of significance.

Propagated by persuasive advocates, this view has gained acceptance in scientific circles and, even, in part of the general public, as being the irrefutable message, however unpalatable, of modern biological knowledge. It has, in turn, evoked an anti-science backlash among the many who, for one reason or another, find the message exceptionable. The favor with which the ‘intelligent design’ theory has been received is partly attributable to this reaction. By making claims that contradict our most intimate convictions, it is contended, science disqualifies itself as a valid approach to the truth.

In my opinion, this conflict is unwarranted, largely because the popularized notion of the total contingency and, hence, meaninglessness of humankind rests on false scientific premises. As I have tried to make clear, there are solid scientific reasons to see the advent of humankind as much more probable than is generally believed, which, in turn, leads to the conclusion that we belong to a Universe in which the generation of intelligent beings is very likely, if not obligatory.

This notion has been defended by some cosmologists and physicists under the name of *anthropic principle*, which is based on a number of calculations showing that if any of the major cosmological constants had values only slightly different from what they are, our Universe would not have produced conditions compatible with the existence of life and mind. Hence the conclusion that we live in a Universe 'made for us'.

The calculations supporting the anthropic principle have not been challenged. But the defenders of cosmic contingency have disputed its significance on the grounds that our Universe could be just one in what the British astronomer Martin Rees (1998) has called a 'multiverse', a huge collection of universes with all kinds of different constants. As chance has it, so this interpretation goes, our Universe happens to have constants suitable for life and mind to arise and so has come to be known. But this, like biological evolution, is a pure matter of chance; it also is meaningless.

As I have explained elsewhere (de Duve, 2002), I do not accept this conclusion. Whatever the number of universes, ours remains, in my opinion, supremely significant. Life and, especially, the human mind, with all it has produced – the sciences, the arts, the philosophies, the religions, the social, political, and ethical systems, in short, all the fruits of civilization and humanism – are such remarkable manifestations that they can be but telling revelations of what I call 'Ultimate Reality'.

In this respect, I accept the premises of the anthropic principle, but not its name, which smacks too much of anthropocentrism. To the human-focused notion of a Universe 'made for us', I prefer the more neutral view that we live in a Universe conducive, by way of life, to the generation of increasingly powerful means of elucidating its secrets and apprehending its mystery. This, to me, is a *meaningful Universe*, even though I find myself unable, with my limited mental abilities, to grasp exactly what this meaning is. Perhaps, some day in the distant future, some beings may do better.

3. *The Responsibility of Humankind*

Even though humankind may be only a stage in an ongoing continuity, its advent represents a watershed. The two are not incompatible. Salamanders walk, fish don't; birds fly, reptiles don't. Yet a continuous chain of intermediates links the ones to the others. What distinguishes us radically from our primate cousins is our ability to *understand* the world and to *manipulate* it accordingly. Especially, it is the *moral responsibility* that goes with this ability.

This realization is recent. Up to a few decades ago, humans, at least those who are identified with the so-called higher civilizations, behaved as though they had been given the world for their indiscriminate enjoyment and exploitation. It is only recently that more far-seeing concerns have started to be voiced on the consequences of human interventions. In answer to these concerns, measures have begun to be taken or are contemplated, even though reluctantly, to protect the environment, avoid pollution, save the remaining forests, shield endangered species, preserve the ozone layer, decrease the emission of hothouse gases, in short to counteract the harmful effects of prior, unrestrained, human plundering of natural resources. Note that, except for a few true 'nature lovers', the motivation behind these concerns and measures is still largely anthropocentric. Only in the face of glaring and serious threats to human welfare or prosperity are restrictions recommended, enforced, and accepted. We still look at the world as our own but are moved to husband it better, the way we would our capital. Even here, however, self-interest stops too often at national boundaries for truly effective actions to be taken. One can only hope that global self-interest will prevail over narrow, local preoccupations before some of the damage inflicted on the environment by human activity reaches the point of no return.

Leaving these matters to the experts and decision makers, I wish to address a new and much more exacting challenge to human responsibility, occasioned by the developments of biotechnology. As of now, we already have the means to engineer life in many ways. The scope, precision, effectiveness, and ease of such interventions are increasing almost daily. Soon, we will be able to modify existing life forms and to create new ones almost at will, thus supplanting natural selection and replacing it by human intentionality, in the direction of evolution, including our own.

All over the world, voices have been raised in alarm at the prospects opened by these new capabilities. The sacredness of nature is invoked. All kinds of ethical safeguards, rules, and laws are clamored for. Powerful bodies, including many governments and the major religions, have demanded that some interventions, such as human cloning, be banned outright and that many others be severely restricted. The more aggressive environmental movements go so far as to resort to violent opposition.

In the face of all this turmoil, one must note first that there will be no going back. Biotechnology is here to stay and will inexorably move forward. Whatever restrictions are imposed, there will always be some exception to allow a new type of experimentation, be it only in a more permissive country. It is significant, in this respect, that the International Bioethics Committee created by UNESCO did not, in its 1997 'Universal Declaration on the Human Genome and Human Rights', proclaim the inviolability of the human genome, contrary to the desire of many of its members.

It must be noted next that the human impact on biological evolution is hardly new. For some 10,000 years, breeding and agriculture have modified animal and plant species to a point that their wild ancestors are hardly recognizable in their modern descendants. More recently, the advances of medicine have begun to change the human gene pool to a significant extent and not always for the better, since harmful genes are now given opportunities for spreading that they did not enjoy before. What has changed is that our means have become much more powerful and, especially, can be applied consciously and deliberately to much more specific and predictable ends.

Finally, we must admit that there is nothing intrinsically bad about trying to improve on nature. The argument that nature is sacred and should not be tampered with is scientifically invalid. 'Mother nature' exists only as a myth. She is neither wise nor benevolent; nor does she have any allegiance to the human species. Scorpions and the AIDS virus are as much objects of its solicitude as are butterflies and poets. Nature is governed entirely by natural selection according to an intricate network of influences that pit the conflicting interests of different organisms against each other (struggle for life) within the constraints imposed by their interdependence (ecosystems). Surely, to substitute *reason* for this blind interplay can hardly be condemned. In fact, such a takeover may be seen as part of the privilege – and burden – of being human.

The only serious problem raised by biotechnological developments is whether we, as humans, possess enough collective *wisdom* for the exercise of our newly gained mastery over the living world. This question is particularly acute as concerns the human applications of biotechnologies, especially at the germ-line level. The current opposition to a new form of *eugen-*

ics is probably justified in this respect. To give our fellow human beings the license to direct future human evolution may well appear to many like giving children a box of matches. Nevertheless, children do get hold of matches and a few even set fire to the house. The others eventually grow wiser and use the matches for good purposes. I have a suspicion that this is what will happen to directed human evolution. Probably, many egregious mistakes will be made. But, some day, our distant successors will put humankind on the right course and lead it on the way to more penetrating intelligence, finer sensibility, greater compassion, and, especially, deeper wisdom. If this does not happen, it will be up to natural selection to start a new, more successful line. There is plenty of time for that.

Final Comments

In this essay, I have endeavored, to the best of my ability and with as much objectivity as I can muster, to clarify, as much for my own benefit as for that of my readers, the manner in which recent scientific advances, especially in the field of biology, affect our perception of the human condition. Not altogether surprisingly, some of my conclusions are not readily reconciled with the traditional image of humankind one derives from the Bible and other sacred writings. It is not for me to decide how this discrepancy will be resolved. I can only, as a scientist, present the established facts, generally accepted theories, and likely surmises allowed by the present state of knowledge.

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DISCUSSION ON THE PAPER BY DE DUVE

LE DOUARIN: Thank you very much for this very stimulating lecture, which is now open to discussion.

COYNE: Just a very direct question based on my ignorance of neurosciences. The emphasis upon the surface area of the cortex, rather than upon the chemical complexity of the content, is it just surface area of the cortex or is it the chemical complexity of what is contained?

DE DUVE: Largely the surface area. But it is not just the cortex. The whole brain has increased in complexity. The brain mass has increased three-fold during the last part of the hominization process; it is three times the mass of the brain of our nearest chimpanzee ancestor six million years ago. I mentioned the cortex, because it is believed to be the seat of consciousness.

COYNE: So the functional complexity of the human brain does not go linearly with the surface area of the cortex, or does it?

DE DUVE: I don't know about linearly. All I can say is that the surface area of the cortex has increased more (four-fold) than the brain mass (three-fold).

COYNE: You said that for the evolution of life certain chemical steps should be highly probable to evolve life. I would suggest that from evolved chemistry to life is probable, not necessarily highly probable.

DE DUVE: I didn't quite say that. My point was that because the origin of life depended on chemical steps and because chemistry depends on deterministic processes, the phenomena that led to life must have been highly probable under the conditions that existed at the time.

COYNE: Yes. And the other question is: you mentioned that for the first eukaryote to evolve on earth we assume that it took 25% of the life of the planet, 2.2 billion years out of 9 billion years.

DE DUVE: The first eukaryotes are believed to have arisen at least 2.2 billion years ago. With life starting about 3.5 billion years ago, perhaps earlier, this means that life may have gone through about one-third of its history before eukaryotes appeared. But all these figures are very rough approximates.

COYNE: So you say about 25% of the life of the planet. My question is: do you think that on other planets it could take much longer than 25%?

DE DUVE: Much longer.

COYNE: Yes, much longer. I mean, life is highly probable on other planets, provided that the first step is not long enough, is not too long.

DE DUVE: Life is probable.

BATTRO: Yes, thank you Professor, your paper was very interesting, but in my profession I do not deal with the double brain but with the half brain, and we can say that it is exactly more or less half the surface, but to test my students I say: in a normal brain we have 10^{12} neurons.

What is the half of 10^{12}? And this is a kind of trap, because mainly, or mostly, they say 10^{6}, which it is not. The half of the brain has an enormous number of neurons. Therefore my interest is: with this half brain some people are very intelligent and some even go to university. Perhaps the question is: what is the minimal architecture we need in order to be intelligent or human? This is a question we can deal with, and I am astonished every day, working with these kids or young men, how much they perform with only half a brain, and therefore I do not know really if we need so much brain to be human. Certainly not, because these persons are human, but what is the minimal architecture you need in order to prove Pythagoras's theorem? This is a scientific question, and I can say that at least half a brain is enough.

DE DUVE: Thank you, I think you are making a very interesting point. But we cannot discuss the details because I am not familiar with them. First of all, when you say half a brain, is it their left brain, their right brain, did they lose it by accident or did they have a complete brain to start with or what?

BATTRO: Normally this is a result of surgery.

DE DUVE: Surgery?

BATTRO: Surgery performed when they were young. They had both hemispheres but because of epilepsy or a tumor one was removed. Professor White is here and he did one of the first hemispherectomies.

DE DUVE: On a young man?

BATTRO: I know one young man who is 18, and he had his left language dominant hemisphere removed when he was 10, and now he is entering college, and we are astonished, it is like saying that the planets move in square orbits. We certainly imagine the plasticity of the brain, which is enormous. Therefore, this kind of experiment of nature shows that you can perform like a perfect, normal being in many cases with only half a brain. What is this brain power? Perhaps it is related not to sheer power but more to the architecture, the intricacies of that. Therefore, and in order to finish this, if we have 10^{12} neurons and you add all the neurons that are in the human species, it is around the Avogadro number. But this number is a very tiny part of all the animal neurons that are on earth today, and these other neurons could some day be transplanted into a human brain in order to provide new tissue for a disabled brain. Therefore I think the way evolution goes is that we can and we will introduce non-human neurons into the human brain. Well, this is not a wild idea; some people are trying to do that too.

DE DUVE: This becomes very technical, so I thank you for your comments. I will just say that half a human brain is not a chimpanzee brain, and what would a chimpanzee do with half a brain?

BATTRO: Well, they also do a lot.

CABIBBO: Well, I have two questions. One has to do just with the size of the brain. Perhaps it is not a question of brain size but really the invention of communication. Efficient communication and language were really a big bang for humanity, and maybe there is nothing comparable in the future, nothing much bigger than that. So, maybe you see that this has shown that we are not working with one brain but with Avogadro's number of neurons.

DE DUVE: The development of language was, of course, a very important step. Some workers believe that it was the development of language that inaugurated what is sometimes called the 'Great Leap Forward', the extraordinary acceleration of cultural evolution that started some 50,000 years ago.

CABIBBO: But language gave such an advantage, because it allowed sharing, conservation, storing, etc. That's one question. The other one I would like very much to examine from the point of view of the necessity of life, cosmic necessity. I think it is not necessary; for all that we know life could be very improbable, it just happens that we are here, I mean, we were lucky, so we cannot really know. Maybe a measure could be when we will be able to start exploring many other planets, or getting into communication with some of them, although it will not prove very much, because maybe these other planets have not waited enough, but it is a statistical thing, we don't know really. I know that my opinion is rather extreme, but even if it is highly improbable, quantum mechanics will make sure that at least in some branches of the quantum universe you do have life, so it's enough that it is possible.

ARBER: I very much appreciated your paper and largely agree with it. If I interpret your statement correctly, I can expect that sooner or later, on some other branches of the evolutionary tree, forms of higher intelligence will develop. Is that your idea too, i.e. not only humans can and will undergo a cultural development? And then the last statement said the future is in our hands. Are you going to cut off these other branches, or are you going to manipulate the human branch? You should tell us what is in our hands. What do you mean by 'the future is in our hands'?

DE DUVE: What I meant is that we now have the ability of knowingly and deliberately shaping the future of life on our planet, including our own future, in a totally unprecedented manner. Already now, the new technologies, especially their application to human beings, are raising many problems. And these problems are nothing against those that will confront coming generations. The increase in our brain power has given us science and the means to apply the discoveries of science. But it may not have given us enough wisdom to handle this power. We may do a lot of good, but also a lot of harm, including possibly causing our own disappearance. This is what I meant by saying that 'the future is in our hands'.

RICŒUR: Yes, my question is about your last sentence. The future, you say, is in our hands. Your whole discourse was the discourse of an observer; but the last sentence is heterogeneous to this discourse. Is it the case that we are responsible?

DE DUVE: Je ne vous comprends pas.

RICŒUR: Je disais que votre dernière phrase est hétérogène par rapport au reste de votre discours qui était celui d'un observateur, et votre dernière phrase, "le futur est dans nos mains", est d'un homme responsable. Vous êtes passé d'un discours descriptif à un discours de prescription, parce que le mot "nos", nos mains, our hands, nos, suppose la possession par un homme responsable de son action. Alors, votre dernière phrase ce n'est pas la conclusion, c'est un autre discours appartenant à une autre région de notre culture que la science.

DE DUVE: Je ne saisis pas la distinction philosophique. Lorsque je dis que l'avenir est dans nos mains, je me contente de faire une constatation. Je ne prescris en rien.

RICŒUR: Non, là il fallait dire le futur est dans ses mains à lui, l'homme dont on a parlé dans la description.

LE DOUARIN: Très bien. Merci pour cette mise au point.

LÉNA: My question is related to the point you made that chance does not exclude inevitability. If we assume, and I agree with you on the likelihood of life in many places in the universe, and possibly in an infinite number of places if the universe is flat, i.e. infinite, as it seems to be now, then the number of sites where life happened can be extremely great: you give a number of the order of 10^{15}, but it could be even higher, and then the occurrence of us is inevitable, is no longer a matter of chance, because almost all of the possible cases will be realised in this random process.

DE DUVE: I won't disagree with that.

JAKI: It seems to me that you take a too optimistic view about the great number of earth-like planets, and consequently on the very high probability of organic and intellectual life elsewhere outside our planetary system. Now, even from the purely biological viewpoint, the origin and development of life on earth heavily depends on the presence of a very strange body called the Moon around it, which is an exceedingly rare occurrence. Now, with respect to the intellectual development of life on earth, especially scientific development, it begins essentially with Greek astronomy, with Aristarchus, Eratosthenes and Ptolemy. For these people the presence of the Moon, a body of a given size, of a certain visual distance is absolutely indispensable for working out their geocentric hypothesis, and those hypotheses were absolutely indispensable for Copernicus; Copernicus was absolutely indispensable for Galileo, Galileo for Newton, and so forth. In other words, if we restrict our consideration of intellectual life on earth, we must conclude that the evolution of science is a most improbable phenomenon largely controlled by the presence of the Moon and we have a moon around the earth through an exceedingly rare glancing collision between the earth at a particular phase of its development and of an unknown body. Now, I am not sure whether you are familiar with the book *Rare Earth* published by two members of the National Academy of Science, which created quite a stir in the United States. Its conclusion is that life elsewhere in our whole galaxy is exceedingly unlikely. One of the authors is an astronomer, the other is a biologist, and they are very prominent people. They say that much of our galaxy is exceedingly hostile to life, and then in that book finally – which is about 330 pages long – there are three pages in which the earth, the bearing of the earth-moon system, is discussed. So, I'm very sorry, but I have to disagree with your optimism on strictly scientific grounds.

DE DUVE: I disagree with you. I have read a few books myself. You certainly know that other astronomers and cosmologists have a different view.

RAO: My first question was covered by him a few minutes ago, but I don't want to be too euphoric about this. You know, the number of human beings who actually use the surface area of their brains is very, very small, so what I wanted to observe is this. You've used probability in all your arguments. Even scientific discoveries have been made by a very small number of people even though the large population of human beings possesses this large surface of the brain. Therefore, having a greater surface doesn't mean more discoveries. I don't think it is a linear function. Second, you mentioned the environmental factors. Werner Arber also said how antibiotics destroyed so many... have made us resistant. Environmental factors and various factors that we are going to create now in this world may have a completely different effect on these happenings, including man becoming brainier and so on. I feel that we have to worry about the environment a bit more, not ignore the environment.

DE DUVE: As you know, this distinction has been made by many people. Relativity, natural selection, the double helix, or whatever was bound to be discovered some day. But the 'Wohltemperiertes Klavier' would never have been composed if Johan Sebastian Bach had not existed. So, there is a big difference between a scientific discovery, which is just finding something that is there to be found (if you don't find it, somebody else will), and a work of art, which is something irreplaceable. Something that depends on the unique brain connections that belonged to Bach, Shakespeare or Leonardo.

ZICHICHI: I would like to thank you for this impressive list of facts on the origin of life. However, I would like to ask you to add a detail, which could be an important fact; namely that if I give you billions of molecules having the same chemical composition, the same understanding that you correctly emphasise, no one would be able to transform this amount of inert molecules into living ones. Your series of impressive facts should have as a scientific consequence two basic points. Firstly, the reproducibility of phenomena. You said we understand the origin of life from the chemical point of view. You should add that nobody is able to transform any amount of inert matter into living matter. This is point number one. Point number two: no one is able to formulate in a mathematical way this impressive series of facts. After two hundred years of experiments in electricity, magnetism and optics, we end up with the Maxwell equation. Your very impressive list, which I appreciated very much, should have two concluding points: one, it lacks experimental reproducibility, i.e. no one is able to transform any amount of inert matter into living matter; second, no one is able to express in a mathematical form the synthesis of this very impressive set of facts. These facts bring me to the third point, which refers to life in the cosmos. The cosmos has existed for twenty billion years. In the cosmos there are, as you know, about a hundred billion galaxies, and each galaxy has on average a hundred billion stars. Our sun exists since just five billion years. There are fifteen billion years already gone for all other stars, billions of billions. Therefore, if life was so easy, why did not other fellows reach what we've been able to reach in ten thousand years, the number of years for our civilisation? These fellows of the cosmos should have been able to send us messages, because they are smarter than us: we are just very young, they are 15 billion years ahead of us. Where are they? They should exist in billions of forms. We have existed for only 5 billion years, but the cosmos has existed for 20 billion years: we have missed 15 billion years, and billions of billions of stars where a civilisation in ten thousand years should have produced an immense amount of smart guys able to communicate with us. You gave us a very fascinating presentation. Please add in your impressive list these three points in order to make the list complete and to ensure that everybody has the complete picture.

DE DUVE: You have said a lot, so it is difficult for me to answer all your questions or remarks. But let us start with the first one. I did not state that life arose naturally. I said this is my working hypothesis, consistent with what we know of the nature of life. It is true that nobody has so far been able to generate life in the laboratory. But, to me, this working hypothesis is the only one that can motivate research. You cannot try to understand something that you believe a priori to be unexplainable. Hundreds of investigators are presently occupied with the problem of the origin of life and have already obtained very interesting results.

As to why other civilisations, if they exist, have not tried to communicate with us, this question, as you know, was already asked by Fermi. There are many answers, including that the best proof of the existence of intelligent extraterrestrials is that they have *not* tried to communicate with us. But that is a joke. In actual fact, many efforts are being made to detect messages from extraterrestrial civilisations. In the United States, there is a special institute for this, the SETI Institute (Search for ExtraTerrestrial Intelligence). An enormous effort is also being devoted to the detection of extrasolar planets that might bear life and, perhaps, intelligence. Of course, astronomical distances are so enormous that the probability of such a search being successful is very small, even if the Universe should be teeming with life and intelligence.

LE DOUARIN: Thank you very much for these very optimistic conclusions. There is one pressing question, the last one, because we are late.

VICUÑA: I think it's clear that this was a very provocative and fascinating lecture. Statement number three: you said that life arose naturally by a large number of chemical, highly probable steps, and from that statement I would deduce that life arose several times on earth, but your first statement says that all living beings are descendants from a single ancestral form. Do you mean then that other forms of life are extinct? Why is it that all living beings descend from a single form if at the same time you say that life arose naturally by a large number of steps whereas according to the laws of chemistry that are deterministic you would expect that life would have arisen several times? That is one question.

DE DUVE: There are many possible answers to your question. It could be that conditions were right for life to start only in one place. Or that incipient life went through a selective bottleneck out of which the universal common ancestor emerged. And so on. My point was that life is a chemical process. When Professor Zichichi tells us that nobody is able to transform inert matter into living matter, that is of course not true. We and all other living organisms do exactly that.

VICUÑA: Dr. de Duve, I agree with you of course that life is explainable in terms of physics and chemistry; it has to be, and we cannot fill the gaps of our ignorance with, you know, religious beliefs or other types of knowledge. Our duty, as scientists, is to try to explain life as a natural phenomenon, irrespective of the type of faith that we may have. So, the question is: I suppose that we already have all the knowledge we need to define life, but why is it that there are so many definitions for life?

DE DUVE: This is because every definition emphasises one aspect, like the elephant in the story. My own definition of life is simple, even simplistic: life is what is common to all living beings. This is not a tautology, because it excludes many things from the definition of life. To be alive, one does not need a brain, or wings, or legs, or green leaves. One does not even need many cells. One does not need mitochondria. What remains is what is indispensable and common to all living beings. This is still quite a lot. If you look at my few remaining brain cells and at the colibacilli in my gut, you will find the same basic chemical components, the same core enzymes, the same central metabolic pathways, the same ATP, the same mechanisms for storing information in DNA, replicating the DNA, transcribing the DNA into RNA, translating the RNA into proteins, the same genetic code, and so on. That is what I call life.