Constraints on the Origin and Evolution of Life[1]

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Resumo

Neste trabalho são descritas as condições de emergência da matéria e da vida na Terra, confrontando as várias teses sobre o tema. Optando por uma via neo-darwinista como critério de compreensão da evolução das espécies, o trabalho sustenta que a eclosão da vida no nosso planeta representa o mais que provável sinal de uma propriedade intrínseca do Universo no seu todo. Ou seja, aponta para a forte possibilidade de existência de múltiplas formas biológicas exteriores à Terra.

As an introduction to my topic, let me quote from the 1970 bestseller *Chance and Necessity,* by the late Jacques Monod. In this "essay on the natural philosophy of modern biology", as the book is subtitled, the celebrated French biologist attempted, as many have done before and after him, to derive some sort of *Weltanschauung* from the science of his day. On the existence of intelligent life on Earth, Monod wrote the famous sentence: "The Universe was not pregnant with life, nor the biosphere with man"[2]. He did not mean this literally, of course, considering that the Universe did give birth to life and the biosphere did give birth to human beings. Birth without pregnancy would imply a miracle, which is certainly not what Monod had in mind. What he meant is that life arose through the combination of highly improbable circumstances, so improbable that life may have arisen only once in the whole history of the Universe and might well, but for a fantastic stroke of luck, never have arisen at all. Given the fact that life did arise, the probability that it would evolve into intelligent beings is once

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again, according to Monod, extremely low. In other words, we owe our existence to the succession of two extremely improbable events, a near--miracle squared, so to speak, a cosmic quirk. And Monod concludes: "Man knows at last that he is alone in the Universe's unfeeling immensity, out of which he emerged only by chance"[3]. Beautiful poetry, but somewhat shaky science. I propose to explain briefly why I disagree with my late friend Jacques Monod[4].

Let us look at the origin of life first. I will do so succinctly, because Monod's view is no longer shared by many scientists today. According to the most recent observations, we have two landmarks. On one hand, there is the evidence that living organisms, most probably primitive bacteria, were already present on Earth some 3.6 billion years ago, perhaps earlier. On the other, there are the many messages, relayed by radiation from outer space or provided directly by the analysis of comets and meteorites, indicating that the Universe is a hotbed of organic syntheses leading, among others, to amino acids and other typical building blocks of life[5]. This "vital dust" permeates the entire Universe and most likely represents the chemical seeds from which life arose. The problem of the origin of life is, how did these simple molecules interact and combine to give rise to the first primitive cells?

There are two possible approaches to this question: bottom-up and top-down. The paradigm of the bottom-up approach is Miller's historical experiment of 1953[6]. He simply attempted to re-create the chemical conditions he believed, on the strength of a hypothetical model developed by his mentor, Harold Urey, to have prevailed in the atmosphere in the early days of our planet. In no way was he trying to make amino acids. They just happened to be made, by processes that may be relates to those now known, from the analysis of meteorites, to operate on some celestial bodies. No other experiment in abiotic chemistry carried out since is so purely of the bottom-up kind. Workers have always had some substance or substances in mind in setting up their experimental conditions. To be true, they have chosen those conditions to be of the kind that might possibly have obtained on the archean Earth, often, however, stretching this compatibility to, or even beyond, the limits of plausibility.

Ideally, the top-down approach starts from existing biochemical processes and tries to reconstruct the simpler ancestral mechanisms from which they could have been derived. It is often assumed that this approach is unlikely to be fruitful because the pathway from abiotic to biotic biogenesis must have involved so many changes that hardly any trace of the early chemistry can have been left in present-day biochemistry[7].

There are, however, reasons to believe that this may not be so[8], in which case origin-of-life research might benefit from a greater input by biochemists than it has enjoyed so far[9]. In the meantime, we can look at the problem in a more general way. To me, the key word here is *chemistry*. Life is a chemical process, which relies entirely, including its all-important informational aspects, on the operation of specific molecules-proteins, nucleic acids, carbohydrates, lipids, and other typical components of living beings. Likewise, the origin of life was an essentially chemical process, or rather a long succession of intricately interwoven chemical processes. Now, chemistry deals with highly deterministic phenomena, which depend on the statistical behaviour of huge numbers of molecules of different kinds and owe hardly anything to chance. Given a specific set of physical-chemical conditions, the same reactions always take place in the same manner. Applying this rule to the origin of life, I conclude that, given the conditions that prevailed on Earth some four billion years ago-or wherever and whenever Earth life originated-the chemical processes that gave rise to life were bound to take place. Given the same conditions elsewhere, life would similarly arise there.

This view is reinforced by the fact that a very large number of steps must have been involved. Something as complex as a living cell cannot possibly have arisen in one shot, or even in a small number of steps. That would require a miracle. Now, if there are a great many steps, the probability of reaching the end of the chain within realistic confines of space and time soon approaches zero if the probability of each individual step is even moderately low[10]. My conclusion, therefore, is, using Monod´s terminology: the Universe *was* pregnant with life. In other words, we belong to a Universe of which life is a necessary component not a freak manifestation. This view implies that if, as a number of astronomers believe, many other Earth-like planets exist in our galaxy and elsewhere in the Universe, these planets are very likely to bear life, in a form not very different in its main chemical features from its form on Earth[11]. I won't expand further on this topic. I believe it to be accepted by a majority of scientists, certainly among biochemists.[12] Let us now look at the second half of Monod's statement, namely that the biosphere was not pregnant with

man or, more generally, with conscious, intelligent beings. Here, Monod is in much better company. The majority opinion among evolutionists today is that, given the enormous number of chance events that have traced the pathway from the common ancestral form of life to the human species, the probability of this outcome must be considered vanishingly small and its reproduction elsewhere extremely unlikely.[13] In the view of these experts, we are indeed alone, as Monod stated. There are, of course, a number of astrophysicists who believe otherwise and have succeeded in obtaining considerable support for the project of searching for extraterrestrial intelligence (SETI)[14]. But few biologists agree with them.

The case for utter contingency is very strong. According to all we know or have good reasons to suspect, every single fork in the tree of life results from the coincidence in time and site between two chance events: an accidental genetic change or rearrangement affecting a given individual in a population, and a set of environmental circumstances allowing the mutant individual to survive and produce progeny.[15]

Between the common ancestral form of all life on Earth and humankind, thousands, if not more, such coincidences must have taken place. The conclusion is thus inescapable that we owe our existence to the succession of a large number of chance events. Hence the view, held by Monod and by a majority of biologists today, that we are the products of an extremely improbable chain of circumstances.

Now, I want to make it clear that I am in no way questioning the first statement. I am not advocating some kind of woolly, holistic, finalistic, anti--Darwinian theory of evolution. I fully subscribe to the neo-Darwinian view, as substantiated and specified by the findings of modern molecular biology. What I am questioning, however, is the inference from chance to improbability. One does not enforce the other. *Chance does not exclude inevitability.* All depends on how many opportunities there are for an event to take place, as compared to its probability of actually taking place. Whatever the odds, an event becomes virtually bound to occur if you give it a sufficient number of trials. A flipped coin has one chance in two of falling on its heads side. But flip it ten times, and the odds of its doing so at least once are 99.9 percent. At roulette, some 250 spins of the wheel are needed to reach the same probability of 99.9 percent for a given number to come out at least once. In a lottery, the probability of a seven-digit number coming out in a single drawing is one in ten million. But with ten million drawings, the probability becomes two in three. And with one hundred million drawings, the probability is 9,999.5 in 10,000, close to certainty.[16]

This will not help you win in a lottery. But things are different in the evolutionary lottery, which is played with millions, often billions or more, of individuals, following each other, generation after generation, over periods of up to several million years. Within such a framework, the probability of a given mutation occurring under conditions conducive to its being retained by natural selection appears as very much higher than is often affirmed on the strength of little more than some kind of gut feeling. It must be stressed that the number of possible mutations is not unlimited. It may be large, but it is finite, limited by the size and structure of genomes. It is often relatively small when compared with the total number of mutations that occur in a given population.[17]

Contrary to a commonly held opinion, evolution rarely has to wait very long for chance to offer a mutation that will be beneficial in a given set of circumstances. More often than not, the mutations are there, waiting, so to speak, for an opportunity to prove useful or, if merely neutral or not overly harmful, to provide a viable alternative that will later be advantageously exploited. What we witness of evolution in action supports this contention. See, for example, how in just a few decades, organisms have become resistant to the substances used to kill them-bacteria to antibiotics, malaria plasmodia to chloroquine, mosquitoes to DDT, and so on. Note that some of these substances do not even exist in nature. It is clear that the resistance mutations did not occur as a response to exposure to the drugs. This would imply some sort of intentionality, which is ruled out by molecular biology. The mutations were always present or happened regularly, and we provided them with an opportunity to flourish by putting the drugs in the environment. Also revealing is the fact that chance can easily be solicited to provide a desired mutation. In the early penicillin days, cultures of the drug-producing mold were exposed to X-rays in the hope that mutants producing larger amounts of penicillin might arise. The yield of the precious drug was multiplied more than twenty-fold by this chancy device. It is a well-known fact among molecular biologists that almost any desired trait compatible with the cells general organization can be elicited in a population of growing cells by sufficiently stringent selection conditions, once again illustrating the enormous potential of chance mutations. In fact, there is now evidence that natural selection has retained a mechanism whereby bacteria

enhance the mutability of parts of their genome under stressful conditions, where survival may depend on some rapid genetic readjustment.[18]

Once we accept mutations as banal rather than improbable, we are led to the conclusion that it is the environment that plays a major role in shaping evolution by providing the conditions under which given genetic changes will be selected. Which brings us back to chance. It is important here to distinguish between what I call horizontal and vertical evolution. Horizontal evolution is the kind that leads to *diversity* without significant change in body plan. Some 750,000 species of insects are known and several millions may exist. But all are insects. Here is where contingency was given an almost free rein, with all sorts of different environments screening all sorts of different variant forms of the insect body plan, thereby opening a multitude of distinct pathways that led, through the vagaries of circumstances, to forms as different as beetles and dragonflies, bees and praying mantises, as well as those astonishing insects that look for all the world like the branch or leaf they sit on. Incidentally, this extravagant profusion of forms is itself proof of the richness of the mutational field.

Things are different when it comes to vertical evolution, the kind that leads to increasing *complexity.* Here, chance enjoys much fewer degrees of freedom with inner constraints playing an increasingly important role. There are not so many ways of moving, for example, from a fish to an amphibian or from a reptile to a mammal, especially if every intermediate stage in this long transformation is to be viable and able to produce adequate progeny under the prevailing conditions. These constraints become all the more stringent the greater the complexity of the developmental program undergoing the changes. Certain directions are thus imposed on further evolution, in spite of the purely fortuitous character of the underlying events. For example, different groups of aquatic animals have evolved different ways of adapting to terrestrial life, each within a separate set of constraints imposed by an existing body plan. Also, in vertical evolution, selective advantages tend to be more fundamental and less linked to trivial environmental factors than in horizontal evolution.

It is impressive that, in both animal and plant evolution, there is a consistent rise in reproductive efficiency, from random, aqueous fertilization and development to increasingly protected forms of embryogenesis. Vertical evolution has successively produced spores, seeds, and, finally, flowers and fruits, in the plant line. Its main innovations in the animal line have been copulation and then the amniotic egg, developing first outside the animal's body, and then inside, with the help first of a marsupial pouch and later of a placenta. These improvements have not prevented each intermediate stage from diversifying its perfectly viable reproductive mode horizontally. Contrary to what is often maintained by critics of the notion of evolutionary complexification, accepting vertical evolution does not imply denying horizontal evolution. Both proceed simultaneously to shape the tree of life. Particularly remarkable, in animal evolution, is the unswerving vertical drive--with horizontal evolution producing side branches all along the way, of course-in the direction of polyneural com plexity. Starting some six hundred million years ago with a necklace of about half a dozen neurones circling the body opening of some primitive jellyfish, the complexity of the nervous system has consistently increased, culminating, in just the last few million years, in the stupendous threefold expansion of the cerebral cortex in the human line. No doubt the environment played an important role in molding the details of this pathway-the change from forest to savannah is often cited as a significant factor in human evolution-but the overriding element, surely, is the fact that a more complex brain is an asset in almost any circumstance. Viewed in this context, the emergence of humankind or, at least, of conscious, intelligent beings, appears as much less improbable than many maintain. Contrary to what Monod stated, the biosphere *was* pregnant with man.

It has become fashionable, almost politically correct, to deny any significance to the emergence of humankind. We are just one little twig on the tree of life, on par with plague bacilli, amoebae, oak trees, puffballs, scorpions, koala bears, and the millions of other species of bacteria protists, plants, fungi, and animals that now exist or have existed in the past. Some even claim that bacteria are superior to us, just because there are more of them or because they can do all kinds of things, such as synthesizing vitamins or thriving in boiling water or in drying brine, that we are unable to accomplish.[19]

This is utter nonsense, of course. Bacteria have not invented the wheel, decorated the walls of the Lascaux caves, written the *Divine Comedy*, composed the *Welltempered Clavier,* discovered relativity or natural selection, or drafted the Ten Commandments or the Bill of Rights. In fact, no living organism other than human beings has accomplished anything approaching such feats, which one must be either deranged or dishonest not to view as

immensely important and significant. The nonsense would be harmless were it not presented as incontrovertible, scientifically established truth, and gleefully relayed by a number of philosophers, social scientists, writers, and journalists who, for some strange reason, appear to take a perverse pleasure in denigrating the human condition. This appeal to science in support of human bashing is, to put it mildly, unwarranted. We may, in some way, appear as a mere twig in the rich canopy of the tree of life. But trim the tree of its canopy and you see that our little twig obviously occupies the top of a trunk that, while continually extending ever more varied branches horizontally, has simultaneously grown vertically, over almost four billion years, in the direction of increasing complexity. To deny this is to deny what to most of us is self-evident. This, however, is no reason for bragging. Our position most likely is temporary. It was occupied three million years ago by a young female primate called Lucy, and six million years ago by the last common ancestor we share with chimpanzees. What form of life will occupy it in the future is anybody's guess. It could well, in fact, go far beyond anybody's capacity to guess. The astronomers tell us that the Earth will be able to sustain life for another five billion years before it becomes engulfed in the fiery expansion of the dying Sun. If the tree of life goes on growing vertically, it may reach more than twice its present height. Extrapolating what has happened until now, this opens the possibility of mental powers that are simply unimaginable to our feeble means.

This development could happen through further growth of the human twig, but it does not have to. There is plenty of time for other twigs to bud and grow, eventually reaching a level much higher than the one we occupy, while the human twig withers. What will happen depends to some extent on us, since we now have the power of decisively influencing the future of life and humankind on Earth. One can only hope that the generations to come will carry out this awesome responsibility with greater wisdom than humankind has done so far.

Notes and References:

1. This text was originally published in the Proceedings of the American Philosophical Society, Vol. 142, N. 4, December 1998, pp. 525-531. It is reproduced with permission of the American Philosophical Society.

2. Jacques Monod, Chance and Necessity, translated from French by A. Wainhouse, New York: Knopf (1971), 145.

3. Ibid., 180.

4. For more details see my *Vital Dust*, New York: Basic Books (1995).

5. See note 3.

6. S.L. Miller, "A Production of Amino Acids under Possible Primitive Earth Conditions", *Science*, vol. 117, pp. 528-29 (1953).

7. Witness this quotation from *The Origin of Life* (Englewood Cliffs, NJ: Prentice Hall, 1973) by S.L. Miller and L. E. Orgel, two of the major experts in the field. Referring to the possibility that "metabolic pathways parallel the corresponding prebiotic syntheses that occurred on the primitive earth", the authors write: "It is not difficult to show that this hypothesis cannot be correct in the majority of cases. Perhaps the strongest evidence comes from a direct comparison of known contemporary biosynthetic pathways with reasonable prebiotic pathways-in general, they do not correspond at all" (p. 185). But what is reasonable?

8. See: C. de Duve, "The RNA World: Before and After?" Gene, vol. 135, pp. 29-31 (1993).

9. My proposal of a "thioester world" is an example. Günter Wächtershäus´s "iron--sulfur world" is another. For details see my Blueprint for a Cell (Burlington NC: Neil Patterson Publishers, Carolina Biological Supply Company, (1991).

10. To set an order of magnitude, a chain of 100 steps, each with a probability of 50 %, has one chance in 2100, or 10 30, of coming to a successful completion. With 200 steps, the chance is one in 10 60. With an individual probability of 10 %, the overall probability for a 100-step process is one in 10 100.

11. This point is implicit in the deterministic view of the origin of life that I defend.

12. Examples are George Wald, who in 1963 alluded to the "dawning realization ... that life in fact is probably a universal phenomenon, bound to occur wherever in the universe conditions permit and sufficient time has elapsed" ("The Origin of Life," in: Philip Handler, ed., *The Scientific Endeavour*, New York: Rockefeller University Press, 1963, pp. 113-34; see p. 120); Albert Lehninger, who in his classic textbook *Biochemistry* (New York: Worth Publishers, Inc., lst edition, 1970, p. 771), visualized the origin of life as "the result of a long chain of single events, so that each stage in their evolution developed from the preceding one by only a very small change", adding "each single step in the evolution of the first cells must have had a .reasonably high probability of happening in terms of the laws of physics and chemistry"; and Manfred Eigen, who expressed the same view even more forcefully in 1971, writing: "We may furthermore conclude that the evolution of life, if it is based on a derivable physical principle, must be considered an *inevitable* process (italics are his), despite its indeterminate course ... it is not only inevitable in principle but also sufficiently probable in a realistic span of time. It requires appropriate environmental conditions (which are not fulfilled everywhere) and their maintenance. These conditions have existed on earth and must still exist on many planets in the universe" ("Self organization of Matter and the Evolution of Biological Macromolecules," *Naturwissenschaften*, vol. 58, pp. 465-523, 1971, see p. 519). Nothing has happened since these various lines were written to make them less relevant today.

13. Following are quotations from three prominent American evolutionists who express their beliefs in no uncertain terms: "the assumption, so freely made by astronomers, physicists, and some biochemists, that once life gets started anywhere, humanoids will eventually and inevitably appear is plainly false" (George Gaylord Sirnpson, *This View of Life*, New York: Harcourt, Brace & World, 1963, p. 267); "An evolutionist is impressed by the incredible improbability of intelligent life ever to have evolved" (Ernst Mayr, *Toward a New Philosophy of Biology*, Cambridge, MA: Harvard University Press, 1988, p. 69); "Wind back the tape of life to the early days of the Burgess Shale, let it play again from an identical starting point, and the chance becomes vanishingly small that anything like human intelligence would grace the replay" (Stephen Jay Gould, *Wonderful Life*, New York: Norton, 1989, p. 14).

14. See: F. Drake and D. Sobel, *Is Anyone Out There?* (New York: Delacorte Press, 1992).

15. As stated, this is true only of microorganisms multiplying by simple division. Things are more complicated in the case of sexual reproduction, but the principle of each evolutionary bifurcation depending on the coincidence between two chance events, one genetic and the other environmental, remains valid.

16. These values are readily computed by considering the probability of the event not occurring. Let this probability be *P*, then the probability of the event actually taking place is: *1- Pn*, in which *n* is the number of trials.

17. As a very rough yardstick for such an estimate, consider the following. The average spontaneous mutation rate, as determined experimentally in bacteria (roughly the error rate of DNA replication throughout the living world), is on the order of 6x10 -10 per base pair per replication (See F. Hutchinson, "Mutagenesis," in: F.C. Reindhardt, ed.-in-chief, *Escherichia coli and Salmonella, Cellular and Molecular Biology*, 2nd Edition, Washington DC: ASM Press, 1996, Vol. 2, pp. 2218-35). On the other hand, the number of possible point mutations (replacement of one base by another) is 3 per base pair. This means that 3/6x10 -10 , or 5x10 9, replications –the number accomplished in one cycle by some 5 mg of dividing bacteria or 50 g of dividing

mammalian cells– suffice for the number of spontaneous mutations to equal the total number of possible point mutations. Needless to say, this does not mean that all possible mutations will take place in just this number of replications. Chance may have some occurring several times, others not at all. Furthermore, not all mutations have the same probability of taking place. Finally many other genetic changes can occur beside simple point mutations. But the main message is clear. Given the huge number of individuals participating in the evolutionary lottery, mutations in most cases are not rare events.

18. Recent discussion of this topic are to be found in articles by B.A. Bridges, in *Nature*, vol. 387, pp. 557-58 (1997) and by E.R. Moxon and D.S. Thaler, ibid., pp. 659-62 (1997).

19. See, for example, *What is Life?* by L. Margulis and D. Sagan (New York: Simon & Schuster, 1995), and *Full House*, by S.J. Gould (New York: Harmony Books, 1996), and my reviews of these two books in *Nature*, vol. 379, p. 409 (1996) and vol. 383, pp. 771-72 (1996). See also Gould´s presentation to this Society, "Redrafting the Tree of Life", *Proc. Amer. Philos*. Soc., vol. 141, pp. 30-54 (1997).