The Gradual Transition from the Non-Living to the Living

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The term "origin" is associated with a beginning, a debut, a birth. Expressions such as "the origin of life" or "the origin of man" suggest unique moments linked to remarkable phenomena. In the following pages, we will attempt to show that, since its birth, the universe has been undergoing a process of self-organization. The appearance of life on Earth represents one of the stages in this process.

This stage shows certain characteristics that make it a subject of wonder that has been identified as such for thousands of years. Even so, it would be a mistake to see only the special characteristics of the phenomenon, to limit oneself to an exclusively reductionist approach. The holistic approach must also be used if one is looking for possible answers to the question of the origin of life and to the subquestions associated with it: "when?," "how?," and "why?"

As we will see, the reply to the question "when?" is the easiest as long as one is very careful to say exactly what one means by the question.

The reply to the question "how?" is, and will no doubt always remain, imprecise, but it is possible to formulate hypotheses and to suggest certain scenarios.

The question "why?" is obviously the most complicated. If life appeared on Earth as the result of an extraordinary set of chances, the question "why?" is without foundation or, more exactly, admits of a simple answer. Paraphrasing Monod, one can say: "An event of minimal probability had a chance to come about on a single occasion," or alternatively: "In the game of cosmic roulette, life won." On the other hand, if the appearance of life is seen as a stage in the process of self-organization already mentioned, the appearance of life perhaps responds to a necessity. In this case, "why?,"

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which is intimately linked with "how?," must be considered in a different perspective.

The Origin of Life

The origin of life is one of the great questions that people have asked themselves since they have become conscious. For thousands of years, the only possible answers to such a question have been mythical or religious. It was only with Greek civilization that a scientific type of response, based on observation, made its appearance. Aristotle envisaged a process of spontaneous generation, thanks to which, in his view, frogs were born from mud. Today, such a statement makes one smile and one is tempted to see in it proof of a lack of judgement. Rather, one should see it as a proof of the great difficulty, then and now, of practicing the experimental method. Although Aristotle was one of the great scientists in the history of humanity, it was beyond his power to carry out an experiment that involved taking a sample of mud in which there was no fertilized frog spawn and making sure that, for an extended period of time, no frog would come and lay its eggs on the sample. In the seventeenth century, the spontaneous generation of frogs and scorpions was still accepted by Van Helmont. With the passing of time, spontaneous generation soon applied only to "microbes," and one had to wait until the nineteenth century for Pasteur to show that the supposed spontaneous generation of microorganisms was itself the result of experimental error.

It is often said that the theory of spontaneous generation definitively passed away as a result of Pasteur's experiments. Nothing could be further from the truth. The theory that microorganisms are born spontaneously before our eyes, from air or effluvia, was in effect abandoned after Pasteur, but his experiments in no way showed that the spontaneous transition from the non-living to the living was impossible or ever had been. In any case, we should note that the rejection of such a hypothesis would inevitably make it impossible to put the question of the origin of life on Earth in scientific terms. If spontaneous generation is rejected, there are only two other possible explanations for the existence of life of Earth. The first are religious or mythical explanations – life is the result of a voluntary act of creation on the part of a transcendent being. The second explanation is qualitatively different in that it leads to rejecting the question itself – life is present on Earth because life, like matter, has always existed in the universe.

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In these circumstances, life on Earth is the consequence of a process of dissemination of seeds of life that, originally, came from elsewhere. This theory, defended at the end of the nineteenth century by Arrhenius and Kelvin, is called panspermism. It cannot be defended today, because everything has led to the conclusion that our universe has undergone, in its distant past, phases in its development characterized by physical conditions incompatible with the existence of any form of life.

Certain contemporary researchers, like Hoyle, Crick, and Orgel, defend a modern version of panspermism. They still believe that there was an initial insemination of the Earth but they do not reject the idea that life itself had an origin. For these authors, this origin did not take place on Earth but elsewhere in the universe. The theory of panspermism in its modern version cannot be refuted, but that does not in any way prove that it is well founded. In any case, the improbable existence of an initial panspermism does not fundamentally change the nature of the problem. Life appeared on Earth or elsewhere through the effect of a mechanism that, if it does not arise from divine creation, can only be the consequence of spontaneous generation. In this way, we will deal with spontaneous generation but in a very different sense from that of Aristotle or Van Helmont. We will envisage the gradual transition from non-living to living. In dealing with this topic, we will emphasize the conceptual aspects associated with the study of a problem of this kind.

It is worth recalling certain observations and theories, and even certain models, all of which touch on geological, chemical, and physical aspects of the problem of the origin of life. In doing so, we will, as far as we can, use non-technical language. The style of this brief account will have to be dogmatic and, thus, anti-scientific. We beg the indulgence of the reader.

The Earth was born some 4.6 billion years ago at the same time as the other components of the solar system. This birth took several scores of millions of years and is described as a phenomenon of accretion, that is to say a phenomenon of the condensation and self-structuring of a cloud of gas and dust. This cloud, known as a solar protonebula, was probably a fragment from an interstellar cloud, similar to those that one can still observe today in our galaxy, and from the heart of which stars (and probably planets) are born.

In the beginning, the young Earth was hot, devoid of an atmosphere and without any oceans. It was so hot that the rocks of which it was formed were soft. This allowed the Earth to take shape. It acquired the almost spherical form in which we know it today and underwent differentiation. This means that dense elements (essentially iron and nickel) migrated toward the center while less dense minerals accumulated in the peripheral zones. Little by little, the structure of concentric spheres (core, mantle, crust) appeared. This structure is dynamic and remains so today. The existence of the earth's magnetic field and plate tectonics and its consequences (volcanic eruptions and earthquakes) are there to remind us of this.

In these earliest times, while the Earth was taking shape, the magnitude of these dynamic phenomena was much greater than it is today. In particular, volcanic eruptions were very violent. Volcanic gases were therefore expelled from the mantle and helped form a gaseous envelope around the Earth. During this early period – let us say the first five hundred million years – accretion was, but at a slower pace. The Earth, like all the other solid bodies (the sun, the other planets, large satellites), attracted smaller bodies that were in unstable orbits around the sun. The result was a very intense bombardment of the young Earth. It was marked by the impact of asteroids, meteorites, and comets. The signs of these impacts were gradually effaced by erosion and by tectonic movements, but one only has to observe the surface of the moon or of Mercury to imagine what this initial bombardment was like.

The asteroids, meteorites, and comets that collided with the Earth disintegrated and released dust and gases. These gases also contributed to the formation of the gaseous envelope around the Earth, which was cooling gradually. Surface pressure and temperature thus became compatible with the existence of liquid water. Water, which up to that time had been in the form of vapor in the gaseous envelope, condensed. Oceans and primitive lakes were formed. They contained, in solution or in suspension, various constituent minerals from the Earth's crust, but also a great variety of molecules initially present in the gaseous envelope. These various molecules were essentially organic, that is to say, molecules containing carbon atoms associated with other atoms, mainly hydrogen, oxygen, nitrogen, and sulphur. These organic molecules were themselves formed from reactions that had taken place in the heart of the gaseous atmosphere under the influence of the ultra-violet rays of the sun and of the solar wind (mainly strongly accelerated protons) and also under the influence of electrical discharges or radiations associated with radioactive disintegration. All these organic molecules are considered to be endogenous, because they came from reactions within the Earth's atmosphere itself. At the same time, the primitive oceans also contained exogenous organic molecules, that is to say, those that originally came from asteroids, comets, and meteorites. In this way, the primitive lakes and oceans became special places within which a great variety of endogenous and exogenous molecules interacted and reacted. By this time, some four hundred or five hundred million years had passed since the beginning of accretion. The primitive oceans had formed, intense volcanic eruptions continued to shake the Earth's crust, less extra-terrestrial objects were falling from the sky, the phenomena of erosion through the evaporation-condensation cycle of water were active, and the phenomena of sedimentation appeared.

It is important to be able to study the oldest sedimentary rocks that bear witness to the state of the Earth in these distant times. To do this, we have to go to Greenland, to a place called Isua, in order to find sedimentary layers 3.8 billion years old. These layers have undergone a very profound metamorphism. Movements of the Earth's crust have caused them to be buried. They underwent high pressures and elevated temperatures. Other movements of the Earth's crust, together with erosion, have caused them to reappear, but profoundly modified and metamorphized. What can these sediments tell us about the origin of life? They can give a very tentative indication that the organic matter present in these sediments may be of biological or, more correctly, biotic origin. Life may have existed on Earth when the Isua sediments were deposited 3.8 billion years ago.

This uncertain information comes from measuring the isotopic ratio of ^{12}C to ^{13}C in the organic sedimentary matter, a ratio that is difficult to interpret because of the intense metamorphism that the Isua sediments have undergone. However, other sedimentary layers more than 3 billion years old, discovered in South Africa, supply more direct and more easily decipherable information.

Life was present on Earth when these sediments accumulated. Fossils and various microorganisms are there to bear witness to this. It is thus certain that the transition from the non-living to the living on the primitive Earth took one billion years at the most, since it could not have begun before the Earth itself existed. There is a certain arbitrary aspect to this choice, because the constituent atoms of the organic molecules that make up these primitive living beings, like those that constitute contemporary living beings, come from nucleosynthesis within the stars of the first generation, stars that lived and had died well before the accretion of the solar system.

If one were to seek an absolute beginning, one would be tempted to make it coincide with the big bang. But one would have to be aware that the singularity of this event is itself in question.

According to an arbitrary choice by the author, the investigation of the origin of life consists of putting questions about the several hundred million years that passed between the formation of the first oceans and the emergence of the first single-celled organisms in the primitive oceans. Among these questions, two are particularly important – "why?" and "how?." We can assume that the preceding pages have gone some way toward replying to the question "when?" Continuing in a brief non-technical manner, we can summarize certain elements of response to the question "how?" while alerting the reader to the fact that these are nothing but conjectures. We do not possess any fossils or other evidence concerning the process of self- structuring that led from the non-living to the living.

When it was several hundred million years old, the Earth was hotter than it is today. Volcanic eruptions were more intense. Bombardment by meteorites and comets was more frequent. The oceans contained numerous dissolved molecules and were the site of many varied chemical reactions. The atmosphere contained dinitrogen (N_2), carbon dioxide (CO_2), water vapor, and other gases in lesser quantities. One should note the absence of oxygen. This resulted in a reduced number of chemical elements in primitive and volcanic surface rocks and in sediments derived from the erosion of these rocks. The chemical possibilities in the primitive oceans, in the primitive atmosphere, and in the primitive hydrothermal sources can be simulated through laboratory experiments. The laws of physical chemistry worked in the same way four billion years ago as they do today, and one could thus suppose that the primitive oceans probably contained most of the constituent molecules of living beings, or, at least, of the "elementary bricks" from which these constituent molecules could initially have formed. In order to be more precise about the nature of these "elementary bricks," we should mention amino-acids, sugars, purine and pyrimidine bases, fatty acids, and many other endogenous and exogenous organic substances. The variety of organic molecules found, for instance, in Murchison's meteorite, proves the effectiveness of abiotic synthesis. The later stages of formation, the assembly of the bricks into macromolecules, and macromelocules into vesicules (for example, Fox's microspheres with their protein wall), can also be simulated in the laboratory. Such simulations confer a satisfactory degree of plausibility in these stages. One can thus imagine, without any great difficulty, the primitive lakes and oceans containing micro-droplets and organic vesicules in suspension. One can also imagine laminated materials like clays or microporous materials like zeolite containing organic matter absorbed between the leaves or in the pores.

All these systems, even though they are very different, show one of the characteristics of living beings: they have boundaries. There is a frontier that enables one to define an external sphere from an internal sphere. This frontier (membrane, sheet of clay, pore wall) allows exchanges of matter and energy between the external and internal spheres. The systems are open in the thermodynamic sense. Within such systems, numerous chemical reactions can take place, reactions that are necessarily different from one system to another because none is identical with its neighbor. The outcomes of these various systems are thus different.

In the process of self-organization, certain of these systems acquired the characteristics of single-celled organisms. The transition from the non-living to the living was accomplished.

This last phrase is deliberately aggressive in its brevity. It is intended to make people fully grasp the enormous leap in complexity that separates the most complex of non-living systems – prepared in a laboratory – from the simplest single-celled organisms that lived in the ancient oceans. The reactions that unfold in a Fox microsphere or in a clay or zeolite microcavity are essentially the result of chance. At most, certain of them are catalyzed, that is to say, favored by other molecules that are already present. On the other hand, the reactions that unfold in a single-celled organism are not the result of chance but are characterized by a very high degree of spatial and temporal organization.

The non-living/living transition certainly implies even more effective catalytic processes. In contemporary living beings, it is mostly enzymes that act as catalysts. The enzymes themselves are present because the information necessary to synthesize them is also there in the form of deoxyribonucleic acid (DNA). Any consideration of the transition from non-living to living cannot avoid the question of the chicken and the egg at the molecular level! In other words: did enzymes come before DNA or DNA before enzymes? The question is particularly complicated because, in contemporary living beings, the synthesis of DNA itself requires the presence of enzymes. Today, there exists another molecule, messenger ribonucleic acid (RNA), that plays the role of carrier, that transports information from DNA to the ribosomes, intracellular structures in which the synthesis of enzymes takes place. In certain cases, fragments of RNA have catalytic properties. On the basis of these observations, certain authors imagine an ancestral living world at the heart of which RNA simultaneously played the roles of genetic code and enzyme. Attractive though this solution is, it is not universally accepted.

Even if one bears in mind this ambivalent role of RNA, and even if one takes into account that geological time allows, because of its great length, the exploration of numerous possibilities, the leap in complexity mentioned above remains great, too great in the opinion of many scientists. Whether one is dealing with the birth of a genetic code or even of molecular energy, or whether one is dealing with the appearance of lipidic membranes or the acquisition of a photosynthetic type of system, all these stages pose extremely difficult problems. It is possible – even probably necessary – not to look for processes that would have led to the simultaneous appearance of all these possibilities. Perfect simultaneity is much too improbable. Nonetheless, if only some of these possibilities were present at a given moment in a given place at the heart of a particular "preliving" organism, it would have been necessary that, through division, this hypothetical preliving organism would transmit its possibilities to its descendents.

Thus, we have come to believe that the formation of even an elementary genetic code is an indispensable early stage. However, what would be the use of such a code if energy had not been brought under control, if it could not be stored and returned when necessary? What would be the use of such a code without enzyme-type catalysts? Very quickly one thus returns to the near necessity of a certain simultaneity in the appearance of several fundamental properties of life.

If one agrees to pose the problem of simultaneity, one has to be ready to, at least partially, repudiate the reductionist approach. This last statement is more brutal than one might think. The essence of twentieth-century scientific progress is linked to the ever

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greater mastery of the reductionist approach. Having said that, it is also necessary to observe that, in the last few years, the holistic approach has gained new patents of nobility. Taking these elements into account, it seems certain today that the problem of the origin of life is a question that cannot be solved through an exclusively reductionist approach.

The transition from "non-living" to "living" obviously implies an evolution through time. Any inquiry about the origin of life must thus be located in an evolutionary perspective and one can justifiably make reference here to Darwin who, long before Oparine or Haldane, explicitly envisaged pre-biological evolution.

This pre-biological evolution can be described as physiochemical evolution. Its mechanisms are different from those of biological evolution. The turn of biological evolution comes when an "almost living" organism acquires a primitive code capable of being modified by mutation or some other mechanism. Biological evolution takes off running when natural selection can work in favor of the best adapted pre-living organisms. If one accepts the transition from the non-living to the living as a process of self-organization, it is, of course, necessary to accept a solution involving continuity between physiochemical evolution acting solely at the level of "the absolutely non-living" and a biological evolution acting solely at the level of "the absolutely living." There is no fundamental conceptual difficulty in envisaging this transition on the basis of contemporary knowledge of molecular biology and of the molecular mechanisms of biological evolution.

Physicochemical evolution and biological evolution are both aspects of the evolution of matter on Earth. Bearing in mind that the birth of the solar system and the appearance of the Earth are themselves stages in an even more general evolution, one has to include the appearance of life within the process of evolution of the universe. If one examines the theoretical models describing the evolution of the Universe since the Big Bang, it is striking to observe the extent to which, as it aged, it became more and more complex. Astrophysicists and cosmologists describe the initial state of the universe as one of complete lack of differentiation. From this great initial disorder, energy and matter were born, but this initial matter was itself very undifferentiated. Later, it organized itself to the extent of forming large quantities of nuclei, then hydrogen atoms, as well as several other light elements. These atoms themselves came together in gigantic agglomerations within which temperatures and pressures were extremely high. Nuclear fusion was unleashed in the first stars, the stars organized in galaxies, the galaxies organized in conglomerations, and the conglomerations organized into superconglomerations. Nuclear fusion generated nuclei much more complex than the hydrogen nucleus and, when the first generation of stars died, often after catastrophic explosions, the great part of the matter of which they were constituted filled interstellar space. These interstellar clouds became more complex in their turn. Dust particles, molecules, and organic molecules took shape. Sometimes, one of these clouds would rapidly become unstable and break into fragments. These still unstable fragments of clouds collided with one another under the influence of gravity, and the accretion of stellar systems occurred. The so-called "second generation stars" were born as were, very probably, the planets, satellites, asteroids, and comets. This is how our solar system was born 4.6 billion years ago, and there is no reason to suppose that this system is unique. Quite the contrary. There are many reasons to think that the solar system is an ordinary stellar system at the heart of a galaxy that is itself part of a very ordinary conglomeration. If one places the transition from non-living to living, as well as subsequent biological evolution, in the context of cosmic evolution, one cannot but be struck by the increasing complexity and by the ever greater degree of structuring in the Universe. One is normally led to put the question: "Why this growing complexity?" Before even replying to this question, it is necessary to make a rapid survey of the theories of physics that allow one to describe phenomena that vary through time.

Newton's laws are often thought of as the archetype of such theories, but it is well known that, as it appears in Newton's laws, time is a parameter. Changing t into $-t$ makes no difference. The application of Newton's laws to the movement of Halley's comet enables one to trace its previous passages and to predict future ones. Newton's laws ignore the difference between past and future.

Contrary to Newton's laws, the second law of thermodynamics introduced a dissymetry into time. If one puts a hot body into contact with a cold one, heat passes from the hot body to the cold one. The process is irreversible. The second law of thermodynamics introduces a difference between before and after. It says that within an isolated system, all spontaneous processes are accompanied by a growth in entropy. But this second law does not help in any way to understand how an open system, such as one that exchanges matter and energy with the external world, is able to organize itself and, in so doing, increase its own entropy. The second law does not help us to understand the emergence of life.

If one seeks to characterize a living organism from the thermodynamic point of view, one is led to insist on its open character but also on the extreme complexity of such an organism. This complexity itself exists, maintains itself, as a result of exchanges of matter and energy between the organism and the world around it.

An open system, far from being in equilibrium, can remain in a stationary state for a long time, but it can also change its state rapidly, after a minor disturbance. The accretion of the solar system, the non-living/living transition, and certain stages in biological macroevolution may perhaps arise from processes of this kind.

The discipline that allows the description and understanding of the evolution of open systems that are far from being in equilibrium is called the thermodynamics of irreversible phenomena. The development of this discipline owes a great deal to the Brussels School of Thermodynamics, directed by Ilya Prigogine. Among other things, thermodynamics allows us to understand why phenomena of coherence appear in the motion of the constituent molecules of a system that is far from being in equilibrium. The molecules develop gregarious behavior! Coherence can also show itself in the appearance of simultaneities at the level of reaction between the constituent molecules of a system (chemical clocks). An open system in disequilibrium can only be understood if it is observed as a whole. The whole is much more than the sum of the parts.

An open system in disequilibrium shows non-linear types of behavior. This means, above all, that if one modifies, if only slightly, the flow of matter or energy between the system and the rest of the universe, the system, that until then was in a so-called stationary state, can pass suddenly to another state, which is also stationary, but which is different from the first. Moreover, nothing allows one to predict what this new state will be. There is a discontinuity in evolution. In other words, the change takes place in an extremely short period of time compared to the duration of the initial stationary state and yet the new state is radically different from the preceding one. These states that are far from equilibrium are frequently highly structured and extremely complicated because of the very coherence that we have already mentioned. Coherence implies interactions between the parts, interdependence, and synergy, factors that all contribute to the complexity.

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The thermodynamics of open systems not in equilibrium constitutes the best and most effective tool to deal, in a unified way, with all the phenomena of self-organization to be found in the history of the universe.

Thermodynamics of this kind not only explain evolution but also the suddenness of certain evolutionary leaps. However, one should not conclude that rapid evolutionary leaps – the accretion of the solar system, the non-living/living transition, biological macroevolution – are identical except for a few details. "Sudden" on the cosmic scale and "sudden" on the biological scale represent different spans of time. The amounts of energy required in cosmic evolution and in the transition from non-living to living are different. Only the reductionist approach enables one to grasp these differences. It is necessary to guard against an excessively globalizing or synthesizing attitude. At the other extreme, it is not possible to deal with the problem of the origin of life by means of an exclusively reductionist approach without being condemned to search endlessly for the additional stage, in a vain desire to find continuity where discontinuity is certainly the rule and not the exception.

It is also necessary to recognize clearly that the evolution of the universe in the direction of greater organization cannot yet be explained in a totally satisfactory fashion. Having said that, one can state that the thermodynamics of open systems in disequelibrium supplies a conceptual framework within which the problem can and must be broached. Open systems in disequilibrium structure themselves spontaneously, and thermodynamics tells us why. Open systems in disequilibrium generate other systems more structured than themselves that, in turn, generate even more structured systems and thermodynamics tells us that there is nothing to prevent this. It tells us that such an evolution is possible, it does not tell us that it is inevitable and, consequently, it does not give an unequivocal reply to the question "why?" It may perhaps be necessary to consider that the changing universe explores numerous "possibilities" and that what is possible becomes inevitable after a long time. It may be necessary to consider, like Davies, that the general laws of physics have yet to be formulated or stated more precisely, laws in which self-structuring is a fundamental feature of the universe. In his recent book, with the provocative title *The Cosmic Blueprint*, Davies writes:

Strong organizing principles – additional laws of physics that refer to the cooperative, collective properties of complex systems, and which cannot be derived from the underlying existing physical laws – remain a challenging but speculative idea. Mysteries such as the origin of life and the progressive nature of evolution encourage the feeling that there are additional principles at work which somehow make it "easier" for systems to discover complex organized states.

Thermodynamics of disequilibrium, chaos theory, bifurcation theory, catastrophe theory, and the theory of fractal varieties are scientific disciplines with multiple connections that are currently experiencing extremely important developments and that have already profoundly altered our perception of the universe. From these disciplines and sister disciplines, new laws and concepts will certainly be born. These laws and concepts will allow us to understand even better the concept of evolution and, consequently, the origin of life, this fascinating stage in cosmic evolution.

In the late twentieth century, developments in science might, no doubt, have reduced the profound pessimism of Monod, but would not have completely reassured the author of *Chance and Necessity*.

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