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Conceptual framework of research on the origin of life on Earth

Introduction

The main assumption held by most scientists about the origin of life on Earth is that life originated from inanimate matter through a spontaneous and gradual increase of molecular complexity.

This view was given a well-known formulation by Alexander Oparin (Oparin, 1924, 1953 and 1957), a brilliant Russian chemist who was influenced both by Darwinian theories and by dialectical materialism. A similar view coming from a quite different context was put forward by J. B. Haldane (Haldane, 1929; 1954; 1967). By definition, this transition to life via prebiotic molecular evolution excludes panspermia (the idea that life on Earth comes from space) and divine intervention. If we look at Figure 1.1 without prejudice, we realize that Oparin's proposition is extremely bold. The idea that molecules, without the help of enzymes or DNA, could spontaneously assemble into molecular structures of increasing complexity, order, and functionality, appears at first sight to go against chemical and thermodynamic common sense. This view, which modern biology generally takes for granted, appears in most college textbooks, specialized literature, and mass media. The background of Figure 1.1 is the continuity principle (Oparin, 1924; De Duve, 1991; Morowitz, 1992; Crick, 1996; Eigen and Winkler-Oswatitisch, 1992; Orgel, 1973; 1994), which sets a gradual continuity from inorganic matter to organic molecules and from these to molecular complexes, up to the onset of cellular life, with no qualitative gap between each stage. In this sense, then, the view expressed in Figure 1.1 is the modern version of a kind of spontaneous generation, although on a sluggish time scale.

In recent times, the challenges of creationists and their attacks on educational institutions in the United States led to some novel scrutiny of this view. There is nothing new in the arguments of the creationists since the writing by William Paley, the Anglican priest who became famous for having introduced one of the

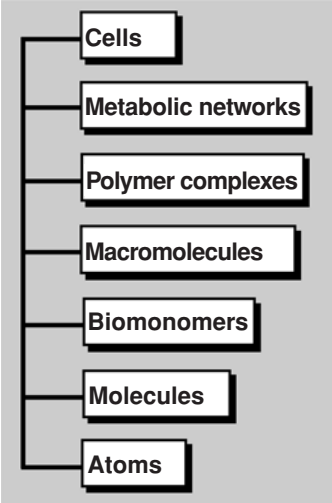

Figure 1.1 An arbitrary scale of complexity towards the emergence of life.

most famous metaphors in the philosophy of science, the image of the watchmaker (Paley, 1802):

> . . . when we come to inspect the watch, we perceive . . . that its several parts are framed and put together for a purpose, e.g. that they are so formed and adjusted as to produce motion, and that motion so regulated as to point out the hour of the day; that if the different parts had been differently shaped from what they are, or placed after any other manner or in any other order than that in which they are placed, either no motion at all would have been carried on in the machine, or none which would have answered the use that is now served by it . . . the inference we think is inevitable, that the watch must have had a maker – that there must have existed, at some time and at some place or other, an artificer or artificers who formed it for the purpose which we find it actually to answer, who comprehended its construction and designed its use.

Living organisms, Paley argued, are even more complicated than watches, thus only an intelligent Designer could have created them, just as only an intelligent watchmaker can make a watch. According to Paley (1802):

> That designer must have been a person. That person is GOD.

As already stated, modern science – even without reaching the extreme reductionism of Richard Dawkins and his Blind Watchmaker (Dawkins, 1990) – does not conform to this view. Paley's metaphor was already negated in his time by Hume and other contemporary philosophers. This does not mean that all scientists are necessarily atheist: the meeting point (the easy one) between science and religion is to accept the idea of a God, who created the beginning and the laws of nature, leaving them

alone to do their job. We will come back to this argument a couple of times in this book.

Creationists apart, the view that life originates by itself from inanimate matter is rich with important implications for the philosophy of science and life at large. It is therefore important in our discussion to pause and consider this view, the underlying conceptual framework, as well as some of the consequences.

Let us start with the concept that is perhaps most important for lay people: it may at first sight appear that once divine intervention is eliminated from the picture, nothing remains except molecules and their interactions to arrive at life. Of course, evolution and interactions with the environment are very important factors, and they can take the fancy form of self-organization and emergence. However, all these factors appear to be based on, or caused by, molecular interactions. In other words, at first sight the acceptance of the view expressed in Figure 1.1 is tantamount to stating that life consists only of molecules and of their interactions.

Is it so? Does a rose consist only of molecules and their interactions? We can answer yes, but it is also fair to say that this would represent only a first, gross approximation. First of all, notice that the term "consists of" does not necessarily imply that life can be *explained* and *understood* in terms of molecules and their interactions. Here comes the age-old question of the discrimination between structure and properties, and whereas the structure per se can be seen as consisting of small parts, usually properties and behavior are not – or at least additional qualitative concepts are needed. In turn, this does not necessarily mean that life holds something intrinsically unexplainable or beyond the reach of science. This is an important and subtle point, and I hope to be able to offer some clarifying ideas about that in the chapter dealing with autopoiesis and cognition.

Let us consider some of the further implications of Figure 1.1. The view that cellular life can be arrived at from inanimate matter may imply in principle the possibility of reproducing it in the lab. Why not, if all we need is a bunch of molecules in a properly reactive environment? This way of thinking is the basis of the experimental work on the origin of life. In fact, the best way to demonstrate the validity of this view would be to make life in the laboratory – the age-old Faustian dream. We do not know how the process of the transition to life really occurred in nature, so how can we reproduce it in the laboratory? The answer to this question is conceptually simple, as pointed out by Eschenmoser and Kisakürek (1996):

> the aim of an experimental aetiological chemistry is not primarily to delineate the pathway along which our (natural) life on earth could have originated, but to provide decisive experimental evidence, through the realization of model systems ('artificial chemical life') that life can arise as a result of the organization of the organic matter.

In other words, since we do not know, each of us is free to choose. Do as you wish so long as you show that it is possible, respecting the prebiotic conditions, to create life from inanimate matter. This is the challenge and the method is open-ended. The ambition of scientists working in the field would be simply to arrive at *minimal life*: a system containing the minimal and sufficient molecular ingredients to be called alive (this notion will be discussed in detail later on in this book). Of course this also calls into question the definition of life, a difficult issue but not an unsolvable one, as we will also see in the next chapter.

Whereas almost all researchers on the origin of life would subscribe to one form or another of Figure 1.1, with life arising from the inanimate matter, they would not agree with each other as to what is the main motor for the upward movement in the ladder of complexity. This point brings us to the next section.

Determinism and contingency in the origin of life

Is the pathway that goes from inanimate to animate matter determined by the laws of physics and chemistry? Or is it due to a unique event resulting from the contingent parameters operating in a particular time/space situation – something that in the old nomenclature would be called chance?

The dichotomy between determinism and contingency is a classic theme in the philosophy of science (see, for example, Atmanspacher and Bishop, 2002) and in this chapter it will be considered only in the restricted framework of the origin of life (see also Luisi, 2003a).

Thus, a deterministic answer assumes that the laws of physics and chemistry have causally and sequentially determined the obligatory series of events leading from inanimate matter to life – that each step is causally linked to the previous one and to the next one by the laws of nature. In principle, in a strictly deterministic situation, the state of a system at any point in time determines the future behavior of the system – with no random influences. In contrast, in a non-deterministic or stochastic system it is not generally possible to predict the future behavior exactly and instead of a linear causal pathway the sequence of steps may be determined by the set of parameters operating at each step.

Considering first the deterministic point of view, we can refer to Christian de Duve (1991); as an authorative example. In his book on the origin of life he writes:

> . . . Given the suitable initial conditions, the emergence of life is highly probable and governed by the laws of chemistry and physics . . .

and later on (de Duve, 2002, p. 55):

. . . I favor the view that life was bound to arise under the physical–chemical conditions that surrounded its birth . . .

The idea of the high probability of the occurrence of life on Earth, although phrased differently and generally with less emphasis, is presented by other significant authors. For instance, H. J. Morowitz in his well-known book on the emergence of cellular life (1992, p. 12), states:

We have no reason to believe that biogenesis was not a series of chemical events subject to all of the laws governing atoms and their interactions.

He also adds, interestingly (p. 3):

Only if we assume that life began by deterministic processes on the planet are we fully able to pursue the understanding of life's origins within the constraints of normative science.

And he concludes (p. 13) with a clear plea against contingency:

We also reject the suggestions of Monod that the origin requires a series of highly improbable events . . .

This seems to lead to the idea that life on Earth was inescapable, and in fact Christian de Duve (2002), referring to a sentence by Monod to the contrary, restates this concept (p. 298):

. . . It is self-evident that the universe was pregnant with life and the biosphere with man. Otherwise, we would not be here. Or else, our presence can be explained only by a miracle . . .

Interestingly, this author, a few pages earlier (p. 289), writing about the evolution of life, has to say:

'Evolution' . . . main mechanism is by natural selection acting on accidental genetic modifications devoid of intentionality. The finding of molecular biology can leave no doubt in this respect.

This complex and apparent set of contradictions testifies to the inherent difficulties of modern scientists in having a clear-cut view of the situation.

However, as I mentioned, the idea that life on Earth can be seen as a deterministic pathway of highly probable and perhaps inevitable events is to be found frequently in the literature. In this regard, I would like to make a general point.

To say that the natural laws may have governed the prebiotic scenario and all that happened in terms of reactivity and transformations, is one thing. To say that the natural laws have constructed a series of causal steps to lead to life, is another matter; in fact, the latter assumes that the determinism is purposely guided towards the formation of life. The natural laws per se do not have a preferential direction,

and actually they move without a purpose – as de Duve also mentioned above – in the direction of the most probable events. In other words, to invoke a guided determinism toward the formation of life would only make sense if the construction of life was demonstrably a preferential, highly probable natural pathway: but this is precisely what we do not know. The statement: "the origin of life must have been highly probable otherwise we would not be here" is certainly not a significant scientific statement. Rather, it is significant, only if we accept that it is based on the unconscious faith that life is unavoidable.

In fact, the same position is taken by a considerable number of the more liberal of creationists (as opposed to the biblical creationists, see Sidebox 1.1), those who accept the idea that God created the world and the natural laws, however let these laws take their own course. Thus, they can accept the science inherent in the natural origin of life, evolution, and Darwinism. Once the natural laws are given, everything develops accordingly, corresponding to a form of determinism. The problem is, that these creationists must assume that God, having created the natural laws, forcibly and purposely directed them towards the construction of life and mankind. In a way, there is an internal contradiction in this view, as one cannot invoke natural laws with corresponding determinism and then force these laws of nature into one preferential channel.

Is there an alternative to this deterministic view? One of the alternatives would be to invoke a miracle, as the one described for example by Hoyle in a famous metaphor (Hoyle, 1983): the accidental building of an airplane by a tornado whirling through a hangar full of spare parts. Rejecting this conjecture, then, de Duve (1991) claims:

> The science of the origin of life has to adopt the deterministic, continuity view – otherwise it would not be possible to adopt a scientific method of inquiry,

echoing the assertions of H. J. Morowitz. This last argument – that we have to adopt the deterministic view, otherwise we are out of business – may sound naïve and tautological, but actually it is tantamount to our definition of science. Science, in its traditionalist and perhaps conservative definition, is the study and interpretation of world phenomenology in terms of the laws of physics and chemistry (with the corollary that science, also by definition, can be seen as a constant internal struggle to expand and overcome its own borders). At any rate, this definition is useful to set a clean, working benchmark between science and non-science. Science is just one part of the human enterprise, and nobody is obliged to belong to the party – but if you do it, you have to accept the more or less uncomfortable definition of science and respect the rules. At this point we should mention the "doc-creationists," those who adhere to the biblical narrative, that the world was created a few thousand years ago in seven days. One is welcome of course to have this world view, and negate all findings of science, but one cannot be a creationist and a scientist at the

same time.[1] Likewise, one cannot claim to be a Christian and refuse at the same time to accept the Gospel. Either one, or the other. Sidebox 1.1, contributed by Margaret Schoeninger, shows the wide diversity of views held within the relatively small creationist movement.

Sidebox 1.1

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The University of California at San Diego

American creationism

In North America a strong attack is being directed toward organic evolution, especially as it relates to humans. Supported by several groups of Christians, largely outside traditionally recognized Christian religions, American Creationism is variable in its arguments although all these rely heavily on the Bible (see excellent review by E. Scott, 2004). Most emphasize biblical literalism but one subset believes Earth is young and another believes Earth is old. The former turns to the Bible for all matters including those involving the physical world. Some groups in the former subset allow for limited microevolution (within species changes) but reject all possibility of macroevolution (transformation of one species into another). For them, humans and apes have independent ancestry and Earth's geology results from a series of catastrophic occurrences like a worldwide flood. Leaders in these movements often come from technical fields like engineering (e.g., Henry Morris of the Institute for Creation Research outside San Diego, California and Walter Brown of the Center for Scientific Creation in Phoenix, Arizona).

Proponents of the second subset, which believes Earth is old (variably), include those who believe that there is a gap in time between sections of the Old Testament accounting for an old Earth, that all of geological history falls within the time before Eden, and the rest is revealed in the Bible. Others believe that the "days" described in Genesis are variable in length (>24 hours), but otherwise everything is revealed in the Bible. Progressives believe that the universe mostly developed according to natural laws, but that God intervened at strategic points along the way with regard to life on Earth. A growing, and increasingly effective group, adheres to the notion of Intelligent Design (well-funded at the Discovery Institute located in Seattle, Washington). In contrast to the other groups, individuals in this group often have post-doctoral degrees

[1] I believe that the main problem of the "doc-creationists" is their inability to distinguish between mythology and religion. To illustrate this I include a short personal anecdote. A few years ago I was involved in a public debate of science versus religion, in a church, with a protestant priest in Switzerland. Father S. started first, and read out to his congregation an old Sumerian legend, 600 years older than our Bible, narrating a universal flood, the birth of a child from a virgin, and other episodes very similar to those in our Bible. And then he said to his congretation: "You see, this is mythology. Let's now get to religion" – leaving me with almost no ammunition. This goes well with the statement by C. von Weizacker who said: *the Bible should be taken either seriously or literarily*.

(some in science) or other professional degrees, some from major universities. Some have faculty positions in major universities (e.g., P. Johnson, an emeritus professor of law at UC Berkeley). This view includes a supernatural, personal Creator that is proven by the presence of order and intricacy or complexity, who initiated and continues to control the process of creation toward some end or purpose. They oppose science as defined by the Arkansas balanced-treatment case in 1982, that Science is (a) guided by natural law, (b) explanatory by reference to natural law, (c) testable against the empirical world, (d) tentative in its conclusions, and (e) falsifiable.

Macroevolutionary processes are accepted in varying degrees, but the key issue is to have an involved, personal creator. In contrast to the preceding groups, one set of Creationists, including the majority of Protestant seminaries and the Catholic Church, believe in Theistic Evolution. The theory holds that there is a Creator who relies on nature's laws to bring about a purpose, that the Bible is not to be taken literally, that science is the method of choice to investigate the world, and that evolution is not seen as a contradiction to theism. In their view, science, which is materialistic in its method of investigation, is independent of the realm of ethics and morals. This latter realm is the concern of responsible social constructs, like religion.

Professor Schoeninger grew up in an academic household in extremely conservative sections of the US (South Carolina and central Florida). Including those formative years, she has lived in 11 of the 50 states. Her BA is from the Florida (southeast), M. A. from the Cincinnati, Ohio (midwest), and Ph. D. from Michigan (midwest). Her faculty positions include: Johns Hopkins Medical School (mid-Atlantic), Harvard (New England), Wisconsin (northern Midwest) and the University of California in San Diego (west coast) plus a postdoctoral position at the University of California in Los Angeles (west coast). Although her major research interest is the "evolution of human diet", perhaps this diverse background explains her fascination with American Creationism.

It is also apparent that the anti-Darwinian movement comes not so much from the present and past Pope, but rather from side-kick zealots – see, for example, the short editorial by Holden (Holden, 2005). As for myself, I would be more sympathetic towards the creationists' camp if experimental evidence were to be provided. It is not difficult to conceive what this should be: simply find *equally old* fossils of horses, dinosaurs, hominids, snails, cynobacteria, and sword fish. As long as this simple evidence is not forthcoming, it is probably safe to be scientifically very sceptical about the creationistic view (in this sense, it is almost funny that the creationists lament some small gaps in the theory of evolution). If you are interested in the creationist movement in Latin America and Mexico, in particular, see the recent article by Lazcano (Lazcano, 2005).

The interesting conjunction in de Duve's and Morowitz's view – and all the others who adhere to the deterministic view of the high probability of the origin of life – is the rejection of the miraculous scenario, and the acceptance, more or

less, of the notion of the inevitability of life under the deterministic laws of physics and chemistry. I maintain that this view is similar to the (more liberal) creationistic view, although not stated expressly by those authors. I will return to this point later in this section.

The claim of the inevitability of life on Earth is criticized by some authors, for example Szathmáry calls it the "gospel of the inevitability" (Szathmáry, 2002), and Lazcano (2003) has similar views. This "inevitability" view has its counterpart in the notion that contingency is the basic creative force for shaping the molecular and evolutionistic constructs on Earth (which de Duve, 2002, dubbed "the gospel of contingency"). It should be said that de Duve accepts contingency, but in a context other than the origin of life (de Duve, 2002).

The contingency view on the origin of life and biological evolution is not new; actually is an old icon in the history of science. One may recall Jacques Monod with his *Chance and Necessity* (Monod, 1971), his colleague François Jacob with *The Possible and the Actual* (Jacob, 1982), and the books by Stephen Jay Gould, who is perhaps the most cited author on contingency in biological evolution (see for example Gould, 1989).

Contingency, in this particular context, can be defined as the simultaneous interplay of several concomitant effects to shape an event in a given space/time situation. In most of the epistemological literature this word has aptly replaced the terms "chance" or "random event" and in fact it has a different texture. In this sense, it should not be confused simply with a "highly improbable event", as mentioned above in the Morowitz citation. For example, a tile falling on your head from a roof can be seen as a chance event, but in fact it is due to the concomitance of many independent factors such as the place where you were, the speed at which you were walking, the state of the roof, the presence of wind, etc.

The same can be said for a crash in the stock market, or the stormy weather on a particular summer's day. Interestingly, each independent factor can actually be seen per se as a deterministic factor: the poor condition of the roof predictably determines some tiles sliding off and falling down. However, the fact that there are so many of these factors, each with an unknown statistical weight, renders the event as a whole unpredictable – a chance event. If the contingent conditions are changed – perhaps only one of them – the final result will be quite different. It may happen a week later, or never. It must be added that this view is not against the laws of physics and chemistry, nor is it equivalent to advancing the idea of a miracle, it is just a stochastic view of the implementation of natural laws.

However, the implications are profound. If we were to start the history of biological evolution all over again, says Stephen Jay Gould (Gould, 1989),

> . . . run the tape again, and the first step from procaryotic to eucaryotic cell may take twelve billions years instead of two,

this implies that the onset of multicellular organisms, including mankind, may have not arisen yet or may never arise. This is contingency in its clearest form. An extreme consequence of this contingency view is Monod's belief (Monod, 1971) that the human species, being a product of contingency, might just as well not have came into existence; hence the famous notion of "being alone in the universe." As a sympathizer of the importance of contingency, I wish to stress that this "being alone in the universe" should not lead one to deduce that the humanistic and ethical values are deprived of meaning, or that the sacredness of life, if you want to call it that, is impoverished. I believe in the contrary, that the values of consciousness and ethics can be arrived at from within the human construct without the need for transcendental sources.

Can one say a final word about this dichotomy contingency/determinism? it would be wise, of course, to avoid the extremes and look for a balance. The image that comes to mind is one used by Maturana and Varela (1998), when discussing the subject of biological evolution; consistently with Kimura's views on evolution, they use the metaphor of water falling from the top of the hill: the flow of water is determined by gravity, by the laws of nature. However the actual path is determined by the accidents on the ground – the trees, grooves, and the rocks encountered on the way, so that the actual downhill flow of water is a balance between the forces of determinism and contingency.

Compromises like this are always useful and make life easier. However, often they fail in the most critical situations. For example, take one fundamental question in the origin of life: is there a transcendental power behind it, or not? It would be nice to find a balance, a hybrid between Scylla and Charybdis, but, unfortunately, this is an either/or situation.

Only one start – or many?

I would now like to consider another question partly related to contingency and determinism: whether life started only once in one particular place on Earth or several times in several places. Probably most "determinists" would say that, since life has a very high probability of arising, there is no reason why it should have started only once and only in one magical place. "Only once" is a notion appealing to "contingentists": if the conditions to start life were the product of contingency – a particular set of chemicals in particular concentrations at particular temperature and pressure and pH etc. . . . – it would be almost impossible to multiply such conditions; this implies that life started only once. This argument is also connected with the question of homochirality, to be discussed later: if life started several times, each time based on contingency, then half of the time we would have one type of homochirality, and half of the time the opposite one. Does the occurrence of only