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Chapter 1

Setting the stage

Introduction

The origin of life on Earth was never a widely discussed issue until the middle of the nineteenth century. In those times, people were pious and good-natured and believed firmly that God has created the world and all living forms, once and for all. It would have been a blasphemy to doubt such a simple truth. And the blasphemy arrived in the form of a book written in 1859 by a British scientist named Charles Darwin, who refused the idea that living forms were fixed, saying instead that they were changing with time, and that they were evolving from a common ancestor. The blasphemy was very convincing and spread rapidly in the scientific community, also contaminating fields beyond biology. Darwin – adding one blasphemy to the other – arrived to postulate, in a letter written to Joseph Dalton Hooker on February 1st of 1871, that life might have originated from natural causes:

> . . . It is often said that all the conditions for the first production of a living organism are now present, which could ever have been present. But if (and oh what a big if) we could conceive in some warm little pond with all sorts of ammonia and phosphoric salts, light, heat, electricity &c. present, that a protein compound was chemically formed, ready to undergo still more complex changes, at the present day such matter would be instantly devoured, or absorbed, which would not have been the case before living creatures were formed.

Thus the idea of the warm little pond, later called prebiotic soup or similar names, was born. And generally, in that time philosophers and biologists were increasingly accepting the idea of an origin of life based on natural laws.

At the time of Darwin, in parallel to the belief in the divine creation, there was also the idea of the spontaneous generation (abiogenesis) of simple life forms. The rationale was that God, in his grandeur, could not have had the time and will to think about the creation of such primitive forms of life. Thus, ants, flies, beetles, mosquitoes, and even rats would originate spontaneously from decaying meat or dirty laundry in the wet cellar.[1] The work of Redi (already in 1668), and by Spallanzani one century later, aimed at providing evidence against abiogenesis, was not convincing to the community of the time. But the work by Louis Pasteur was: people after him accepted that life does not arise by spontaneous generation; life arises only from life itself. This statement, by a trait of irony, seemed to give more strength to the belief that life can only come from God.

1.1 The secular view on the origin of life

However, around the middle of the nineteenth century, the time was ripe for the idea of the secular origin of life. Thus, while Darwin's theories were spreading, the German biologist and philosopher Friedrich Rolle was writing in 1863:

> The hypothesis of an original emergence of life from inanimate matter [. . .] can at least offer the advantage of explaining natural things by natural pathways, thus avoiding the invocation of miracles, which are actually in contradiction with the foundations of science.

Darwin himself was not directly interested in the origin of life, but some of his contemporary scientists popularized his views of a natural origin of life, most notably Ernst Häckel. He stressed that there is no difference in quality between the inanimate and the animate world (*Anorgane und Organismen*) and that, therefore, there is a natural and continuous flux from the one to the other (Häckel, 1866). This "continuity principle" had been advocated also by the already cited Rolle (1863) and by William Thierry Pryer (1880) and is part of the modern view of life.

Proceeding with the historical discourse, let us consider a surprising definition given by Friedrich Engels (yes, the same Engels of Karl Marx's memory), written in *Dialectics of Nature* (1883):

> Life is the mode of existence of protein bodies, the essential element of which consists in *continual metabolic interchange with the natural environment outside them*, and which ceases with the cessation of this metabolism, bringing about the decomposition of the protein.[2]

This is indeed surprising, given the early date and the fact that Friedrich Engels certainly was not a biologist, and that at this time nobody had a clear notion of what "protein bodies" really meant (although Darwin himself had

[1] Famous is the experiment introduced by Jean-Baptiste van Helmont (1577–1644). He suggested that mice are spontaneously generated from wheat. Van Helmont believed it was human sweat which provided the generating principle of life and hence his experiments needed dirty shirts as well as wheat germ and 21 days of fermentation after which the vapors from the shirt with the vapors from the seeds would generate live mice. Van Helmont was surprised to find that such mice were exact replicas of natural mice originating from mouse parents.

[2] A few years before, Engels gave an almost similar definition: "*Life is a mode of existence of protoplasm* and consists essentially in the constant renewal of the chemical constituents of this substance. Protoplasm is here understood in the modern chemical sense and comprises under this name all substances analogous to the white of an egg, otherwise called protein substances" (Engels, 1877). Later, he updated again his definition: "Life is the existence form of proteic structures, and this existence form consists essentially *in the constant self-renewal of the chemical components of these structures*" (Engels, 1894).

spoken of a "protein compound"). Moreover, he pointed out the constant self-renewal of the chemical components of these proteic structures.

We had to wait over 50 years to have a more scientific rendering of Engels' concept. Let's consider a definition written by Perret in the early 1950s, and reiterated by John Desmond Bernal in 1965:

> Life is a potentially self-perpetuating system of linked organic reactions, catalyzed stepwise and almost isothermally by complex and specific organic catalysts which are themselves produced by the system.

Bernal discusses this concept in more detail in his other books (Bernal, 1951; 1967; 1971).

In jumping from Engels to Bernal, we should not forget a big name in between them, Alexander I. Oparin. The question of the origin of life became a scientific issue only with the publication of Oparin's books. However, the first one, *Proiskhozhdenie Zhizni* (Origin of Life), published in Russian in 1924, was largely unnoticed until it was translated after 1950. His second book on this subject, *Vozniknovenie zhizni na zemle* (The origin of life on Earth), published in Russian in 1936, expanded and modified his earlier views in some important ways[3]. It was published in English in 1938 as *The Origin of Life*. The second edition of this book (1941) was published in English in 1953.[4] The reworked and much enlarged third Russian edition (1957) was translated in English in the same year as *The Origin of Life on the Earth*.

He subsequently wrote *Life: Its Nature, Origin, and Development* (1961). The Russian edition was published in 1960, in which he gave a description of life

[3] In his book of 1936, Oparin expressed his views in the form of a dialectical materialist analysis, explicitly citing Friedrich Engels. He described life as a naturally emergent stage in the evolution of matter, one in which physicochemical laws had been supplemented by the "purely biological" laws of natural selection and metabolism. Oparin drew more heavily on the current international literature in astronomy, geochemistry, organic chemistry, plant enzymology, and about the chemical evolution of the biosphere. Stanley L. Miller and H. James Cleaves wrote: "Careful reading of Oparin's 1924 pamphlet shows that, in contrast to common belief, at first he did not assume an anoxic primitive atmosphere. In his original scenario he argued that while some carbides, that is, carbon-metal compounds, extruded from the young Earth's interior would react with water vapor leading to hydrocarbons, others would be oxidized to form aldehydes, alcohols, and ketones [. . .] Oparin's ideas were further elaborated in a more extensive book published with the same title in Russian in 1936. In this new book his original proposal was revised, leading to the assumption of a highly reducing milieu in which iron carbides of geological origin would react with steam to form hydrocarbons. Their oxidation would yield alcohols, ketones, aldehydes, and so on, which would then react with ammonia to form amines, amides, and ammonium salts. The resulting protein-like compounds and other molecules would form a hot, dilute soup, which would aggregate to form colloidal systems, that is, coacervates, from which the first heterotrophic microbes evolved" (Miller and Cleaves, 2007).

Moreover, Oparin drew upon studies on colloidal coacervation, arguing that the formation of coacervate droplets by the electrostatic attraction of organic soils in the early seas provided a key requirement for the emergence of life: chemical pools separated by a membrane from the surrounding medium. Such droplets could selectively assimilate materials, and collect and accumulate catalysts and promoters that would accelerate chemical reactions. Although most of these coacervates were short-lived, Oparin believed that those with the fastest rates of reaction, the most stable internal configurations, and the ability to grow and divide most rapidly, would begin to undergo natural selection, leading to more organized forms and eventually to primitive living systems.

[4] I highly recommend reading the *Introduction* to the 1938 English edition of Oparin's book, written by Sergius Morgulis, editor and translator, as it is still one of the best analyses on the naturalistic essence of life and the progress from non-life to life.

based on six properties: (1) capability of the exchange of materials with the surrounding medium; (2) capability of growth; (3) capability of population growth (multiplication); (4) capability of self-reproduction; (5) capability of movement; (6) capability of being excited. He also added some additional properties, such as the existence of a membrane (a cardinal principle for him); and the interdependency with the milieu (Oparin, 1961). An enumeration of properties, as Oparin does, appears to be the preferred way of getting around the problem of giving a definition in a nutshell, and modern examples of this are given by Koshland (2002) and by Oró (in Schopf, 2002).

However, the list of properties of life may be extremely long and subjective, and the real point is to find the unique feature of life that gives rise to the list of properties (this is what we will do in the next part of this book).

The definition of life is a rather thorny question. About that, let me add that the term *definition* – with its strong ontological flavor – is perhaps too ambitious: the term "operational description" probably catches better the epistemic and pragmatic aspects of the question. As Primas says in a different context (1998):

> . . . by contrast an operational description refers to empirical observations obtained by some pattern recognition methods which concentrate on those aspects we consider as relevant.

Actually, most of the "definitions" of life given in the literature comply with the above operational description.

There are plenty of them; for example, one may refer to those listed in the monographs by Folsome (1979), Chyba and McDonald (1995), or in a book edited by the late Martino Rizzotti (Rizzotti, 1996). See also Popa (2004). In addition, a few dozen definitions of life are given in over 40 pages by a corresponding number of authors in the book edited by Palyi *et al.* (2002). Out of this vast repertoire, I would like to mention some of the least traditional; for example, Alec Schaerer (2002) approaches the conceptual conditions for conceiving and describing life, including the aspects of language, cognition, and consciousness. Or the paper by Kunio Kawamura (2002), who approaches the origin of life from the angle of "subjectivity," referring to the philosophical work by Imanishi (for me, there are strong ties here with the view of autopoiesis, which we will explore in depth later in this book). This author provides a view of life from the classic Japanese philosophical view, with the notion of *shutaisei* (subjectivity). And, still in the same book, you will find the Vedanta view of life (Apte, 2002) as well as that of the Russian Orthodox tradition (Arinin, 2002). There are questions about life raised by other authors and researchers: "Is life reducible to complexity?" (Abel, 2002); "When did life became cyclic?" (Boiteau *et al.*, 2002); "Does biotic life exist?" (Valenzuela, 2002).

I mention these less traditional points of view not because we learn much about the origin of life from them, but rather to emphasize that, by asking the question, we are necessarily dealing with a broad spectrum of perspectives and diverse human cultures.

One cannot end this part on life definitions without mentioning the so-called "NASA definition of life." Originally, this was simply an operational perspective used by the Exobiology Program within the National Aeronautics and Space Administration – a general working definition. However, people working on the origin of life often use this definition –actually proposed earlier by Horowitz and Miller (1962) – which is as follows (Joyce, 1994):

Life is a self-sustained chemical system capable of undergoing Darwinian evolution.

This operative definition is one of the most popular, and probably it is so because it is based on a pragmatic operation. If NASA astronauts are going to find in some distant planet a colony of bacteria that behave just like a terrestrial colony of bacteria, they are going to communicate back that yes, they have found life. However, it is at this point that one would ask them, "Yes, but what is life?"

In fact, the above definition in my opinion is not very useful, nor correct from an epistemic point of view. It applies to populations (Darwinian), and is completely silent if you consider a single living organism at a time – a flying bird, a swimming fish, an oak tree, or a product of synthetic biology. Particularly in the last case, but also for an object found in a distant planet, the genetic background may be unknown or technically impossible to establish. We need a local, "here and now" life criterion to discriminate between the living and the non-living without waiting for evolution or reproduction.

The multiplicity of views presented in literature is thus impressive, and also impressive is the number of books devoted to the origin of life, which I listed to the best of my knowledge (see Side Box 1.1).

The popularity of the NASA definition among the scientists studying the origin of life reflects the obvious prejudice that the molecular mechanism of nucleic acids must be the main basis for defining life. Accordingly, this would bring life and evolution to equivalence.

Considering the overlap between evolution and life, one may recall the distinction made by Szathmáry (2002) between the units of life and the units of evolution. The author emphasizes that the two domains (life and evolution) may partly overlap, but that they should be considered as two distinct realms. Other authors emphasize the same concepts (Lewontin, 1970; Maynard-Smith and Szathmáry, 1995; Okasha, 2006).

Before looking deeper at Oparin's ideas, however, we need to present the scenario of the origin of life in terms of basic data.

Side Box 1.1

Books on the origin of life

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1.2 A few accepted facts

Let us begin by saying that, according to the big-bang theory, the age of the universe is estimated to be 13.8 Gya (billion years ago), while the origin of the solar system, and our Earth, dates to 4.5–4.6 Gya. They say that at this time our planet was more or less a fireball, which reached a certain geological and thermal stability about 4

Gya, at the time of a faint young sun. This is also the age of the first rocks on our planet, as well the age of the oceans. Evidence of oxygen production is at 2.7 Gya, but bacterial photosynthesis was operative long before the atmosphere originated – that is, until 0.6 billion years passed and much more oxygen was being produced, a development for which we do not know the reason.

The most ancient microfossils have been described by J. W. Schopf from the Apex Chert in Marble Bar, in western Australia (Schopf, 1993, 1998; Schopf and Klein, 1992). They are dated 3.465 Gya. The microfossils of Swaziland (Sud Africa) are more or less of the same period. The so-called Gunflin Chert of North America (1.9–2.3 Gya) and the microfossils of the Belcher Group in Canada were the first to be ascribed to the Precambrian period. Readers can find more information about microfossils at http://www.uni-muenster.de/GeoPalaeontologie/Palaeo/Palbot_2011/forschung.html.

Although Schopf's interpretations have been criticized (Brasier *et al.*, 2002), the general consensus today is still that unicellular organisms existed on our Earth at 3.4 to 3.5 Gya.

If these unicellular organisms already had a full-fledged genome, one is tempted to suggest that life cannot have started right away with such a complexity, and that therefore, the "origin of life" must be older than 3.5 Gya. In this regard, consider a quite recent paper by Bell et al. (2015). These authors have analyzed inclusion of graphite in zirconium crystals, and state that the carbon isotope ratio is "consistent with a biogenic origin and may be evidence that a terrestrial biosphere had emerged by 4.1 Gya, or ~300 My earlier than has been previously proposed."

The general view can be schematized as in Figure 1.1, which indicates main events that took place in our past on a time scale. Among these, the position of the plausible transition to life can be located between 3.5 and 4 Gya.

Where should we set the scenario for the origin of life? As we will argue later, the aqueous environment of the ocean is the most accepted scenario, often in the form of tides, which may increase the solute local concentration when withdrawing, with a possible localized scenario such as hydrothermal pools or small lagoons, or even coastal lakes. If life started only in one place and only once, it must have been a place from where it could then rapidly expand and "infect" large parts of the Earth.

1.3 Oparin's view, and its implications

As already mentioned, the view of the origin of life by a natural process, in conformity with the natural laws, was given by Alexander Oparin (1924; 1953; 1957), the brilliant Russian chemist who was influenced both by Darwinian

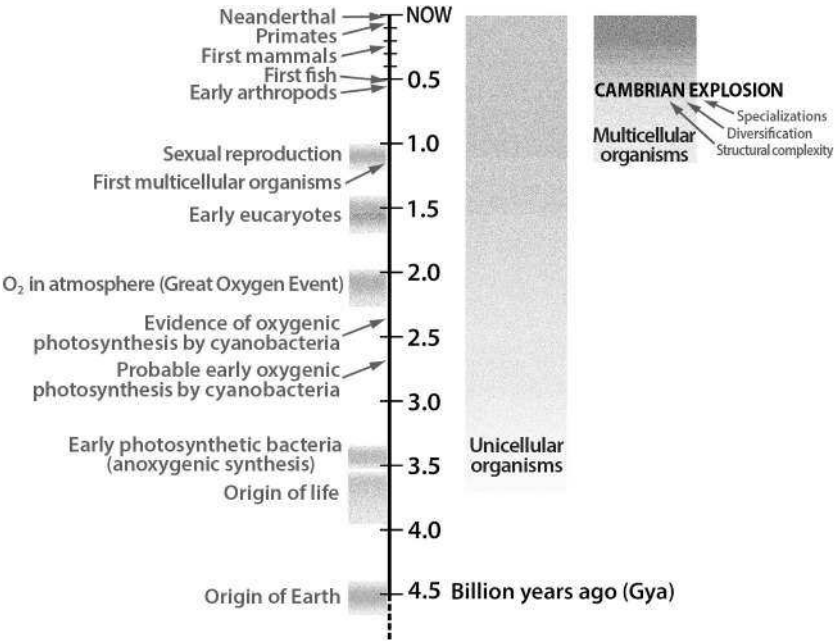

Figure 1.1 A simplified time scale of main events in the origin of life. These "steps" were among Gould's arguments in favor of contingency, as discussed later on in this chapter (Section 1.4). The plausible transition to life can be located between 3.5 and 4 billion years ago. The early eukaryotic organisms appeared around 1.6 Gya and the first simple multicellular organisms circa 1.2 Gya. Note also the Cambrian explosion around 540 million years ago. Prior to the Cambrian event, living organisms were simple, small, and, mostly, unicellular. Maybe, some complex, multicellular organisms gradually became more common in the years preceding the Cambrian, but it was not until this period that mineralized – that is, readily fossilized – organisms became common. Anyhow, the – more or less rapid – diversification of a wide variety of complex multicellular life forms in the first Cambrian produced the first representatives of modern phyla.

theories and by dialectical materialism. J. B. Haldane (1929; 1954) put forward a similar view on the origin of life, coming from a quite different context. Accordingly, there is a natural and spontaneous increase of molecular complexity, governed by the natural laws, up to the point in which spherical compartments – the first cells or protocells – were formed, which could make copies of themselves.

Oparin's view, which modern biology generally takes for granted, appears in most college textbooks, specialized literature, and mass media. The background of the left panel of Figure 1.2 is the already mentioned "continuity principle" (Oparin, 1924; Orgel, 1973 and 1994; de Duve, 1991; Eigen and Winkler-Oswatitisch, 1992; Morowitz, 1992; Crick, 1996). This sets a gradual continuity from inorganic matter to organic molecules and from these to molecular