

## Physical Aspects of the Origin and Early Evolution of Life

Rob Hengeveld\*

*\*Extraordinarius Vrije Universiteit, Amsterdam, The Netherlands.*

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### ABSTRACT

Since there is no information about life's early chemistry, this article reviews aspects of the physics of the origin of life and its first evolutionary steps. Moreover, the chemistry of the ancient environment in which life arose and to which it responded, differed enormously from the present one. Choosing the physics of the earliest steps life could have taken allows a bottom-up approach from first principles.

### INTRODUCTION

Nothing is left of the first compounds from which all life developed. Also, concerning a different environment to which they responded, these compounds will have evolved from primitive and slow reactions to highly complex and dynamic reactions in later ones, which changed their identity. We need to follow a methodology different from that of reconstructing life from present biochemical and environmental properties. This incomparability of life forms in conjunction with their environment forces us to adopt a physical approach [1]. Starting from first principles, it follows a bottom-up reasoning with check points along the way.

### BIOCHEMICAL APPROACHES

Popa [2] found 99 criteria in the literature, presumably defining life. These criteria are based on properties considered typical of, or even essential to, all living systems, and, hence, for reconstructing its origin [3]. However, most properties, if not all of them, can only be generated and maintained by an exceedingly complex biochemical system; they operate within it, rather than solitarily. Two of those criteria, DNA and reproduction, are obvious examples; they can only develop and function in complex systems. The problem of the origin of life is a system problem: how can a system form from scratch, both internally and externally together with its environment [4-6]? Also, in systems elements and compounds, or even complete structures, can in principle be exchanged or be supplemented by other ones without the system stopping to operate. Moreover, the systems approach emphasizes the role of energy, which the chemical approach usually leaves out.

Morowitz [7] and more recently, Lane [8] did put this role central to his argument, but concentrated, again, on complex

biochemical structures and processes typical of evolutionarily advanced stages [9].

Instead, I put the flow of energy and its possible origin and evolution central, chemical attributes secondary. This energy flow is not typical for life processes, but it is essential: living structures are energy-processing systems in which incoming high-energy quanta, such as light, are degraded into multiple, low-energy quanta, heat, which are expelled into space. Chemical materials are recycled, a process driven by a flow of degrading energy. Material recycling is also not typical but it is essential for keeping processes going in a confined space, be they a tiny tube or a cell or the whole Earth. Energy cannot be destroyed, it degrades, whereas matter recycles or decays.

### ENTROPIC DECAY

Entropic decay rules the universe: eventually, all structures, from subatomic ones to galaxies, decay into heat: order turns into disorder. Also, all chemical reactions ultimately release energy as heat, which dissipates into space. This means, conversely, that it costs energy to generate and maintain order, energy which has first to be released elsewhere. Inevitably, the net amount of disorder increases, so that, only at the expense of energy, order can increase locally. This is a fundamental law of thermodynamics applicable to any

**Corresponding author:** Rob Hengeveld, Former Research Scientist, First, at the Netherlands Institute of Ecology of the Royal Dutch Academy of Sciences and, later, at Alterra, a State Research Institute for the Conservation of Nature, Knoppersweg 11, 6668AT Randwijk, The Netherlands, Tel: +31 (0)488 491357; E-mail: rob.hengeveld@gmail.com

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process, also to that of life. Life is a system in which, at high energy costs, an exceedingly high complex process once started, maintaining itself ever since; reproduction counteracts its structural decay. During evolution, the system's complexity and its accompanying dynamic, and hence, the rate of energy flow, increased considerably. The living system's repeated build up and maintenance thus enhances the rate of entropic decay.

Initially, the then unorganised energy flow must have started up as a tiny, low-rate current. But how? Russell and Hall [10] reasoned that water from a basaltic seafloor, containing non-metallic elements, may have trickled into the acid, metal-rich water of the ancient ocean. Hereby, a tube-like crust will have formed at the interphase round the flow, making a partition between the fluids. As in a battery, this caused a flow of energy-rich electrons from outside to inside the tiny tube. From their very earliest stage, therefore, living systems were intimately connected with their environment, as one system. They obtained their energy and, later, also their materials from it, and returned them as contaminating waste. Furthermore, as the enhancing rate of the energy flow intensified, so did the recycling rate. The question remains which chemicals could most likely have been formed, broken up and rebuilt within this confined space in a continuous recycling process, driven by this flux of degrading energy?

#### ELEMENTARY BUILD UP

Traditionally, the non-metallic elements, C, H, O, N, S and P, are considered typical and essential for life. However, the way they operate could, as above, be the outcome of a long evolutionary development. However, quite different, inorganic elements may have composed the initial systems, and these operated under different environmental conditions. Indeed, carbon, nitrogen and oxygen form carbohydrates and proteins, kinetically and metabolically the most stable compounds, and are thus the least likely to initiate a recycling system that has no enzymes. Enzymes only function within a highly evolved, exceedingly complex, and very energy demanding biochemical system. To be formed and to function, enzymes to be formed themselves require other enzymes as well as a stable genetic reference system.

The Periodic Table of Elements shows trends of increasing metallicity - electronegativity - both from the top to the bottom and from right to left. Thus, the lower left hand corner contains elements that most easily donate electrons, whereas the non-metals, forming a triangle at the top right hand, are electron acceptors. Depending on the difference in their electronegativity, these non-metals can make stable, covalent bonds in complex compounds. Metals cannot form compounds with each other - they form alloys with reversible equilibrium, whereas non-metals can, as they also can with metals. Typical for living systems, non-metals will have been present in the trickle on the ocean floor, whereas the metals occurred in the surrounding seawater.

Carbon, nitrogen, oxygen and fluorine, the strongest electron acceptors, form the upper row of the triangle, whereas selenium forms the tip at the base. Selenium both donates and accepts electrons, a property it shares with hydrogen. Under the early anaerobic conditions,  $\text{H}_2\text{Se}$ , as the simplest of their compounds, could therefore most likely have formed the first recycling system, just because of their relative instability. Also, selenium and its compounds are capable of catenation, although less than sulphur, above it in the same period. Over evolutionary time, the system tended towards increased kinetic stability, requiring more energy for its reactions, a development during which selenium may soon have lost its early metabolic position to sulphur. Later, the same happened to sulphur, as it was partly replaced by oxygen, also in the same period. For example, Photosystem I, as the oldest, initially obtained electrons from minerals as donors, such as sulphur compounds, whereas Photosystem II, its modified form that subsequently evolved, obtained electrons by splitting water into hydrogen and oxygen. Photosystem II lifts electrons up from the positive redox level of ca. +820 mV at the membrane, at which  $\text{H}_2\text{O}$  is oxidised into  $\frac{1}{2} \text{O}_2 + 2\text{e}^-$ . From an intermediate redox level, Photosystem I then lifts them further to a negative redox level of ca. -320 mV, comparable to that of ancient conditions and still apparent in the redox value of the cytosol of present-day cells at which the electron carrier NADH is reduced into  $\text{NAD}^+ + 2\text{e}^-$ . Here, in the cytosol the ancient reactions keep taking place. This process is known as the Z-scheme of phototrophy, which freed living systems from their dependence on the surrounding metals of the initial battery system.

The thiol compounds which sulphur formed, with -SH instead of the -OH group of the alcohols, gave their name to de Duve's Thioester World [11]. This presumably predated the phosphate-based RNA World. Initially,  $\text{HS}^-$ , dissolved in water, allowed for energy metabolism and element transfer. Pyrophosphates carried energy from outside the cell boundary into the cell, and were required even before complex biomolecules could be formed [12], whereas later, RNA, consisting of phosphates, also formed the earliest enzymes [13]. Subsequently, DNA as a reference molecule, formed by a stabilisation of RNA, gave rise to the DNA World [14]. In proteins, nitrogen, above phosphorus in the same elemental period, took over part of its enzymatic functions, mostly as part of metalloenzymes. These are still utilising ancient, catalytically active divalent transition metals and evolving in the order of increasing binding strength and compound stability. This order follows the Irving-Williams series running from calcium and magnesium, that form the weakest complexes, to ferrous iron and manganese, then to nickel and cobalt, and finally to copper and zinc that form the tightest complexes [6,14]. Living systems are positively electronegative: over time, they are ever stronger reducing systems taking electrons

from the environment, which as a consequence grows more oxidised.

Thus, following trends in the Periodic Table, the elementary build-up of the system over evolutionary time tended inevitably towards an increasing chemical stability, complexity and dynamic, all at an ever greater energy cost. As they grew, systems also become more conservative, and this had grave evolutionary consequences. The first life forms with their primitive systems may have responded directly to changes in the environment [4-6], before a demographic stage in which systems themselves became components of a new, higher-level system. These inevitable changes within cells can determine attributes of demographic significance between new, supra-cellular systems, such as species, interacting with each other according to Darwinian, demographic selection. Meanwhile, within the cell system and between cells within highly integrated multicellular organisms, evolutionary changes keep taking place, giving rise to new biochemical processes and cell structures of potential demographic significance. Another consequence of the increasing conservatism of systems is that the relative importance of interactions between material components grew over a long evolutionary time; we call this information. In human society, information is finally becoming a component independent of matter.

#### INTERNAL AND EXTERNAL STABILITY

Despite the radical evolutionary changes described in the preceding paragraph, the principle of backward compatibility of computer science holds: keep the basic system structure unimpaired. Thus, the structure of Photosystems I and II is roughly equivalent, and so are the elements involved: sulphur and oxygen occur in the same elemental period. Due to the great amount of energy released by splitting the energy-rich bond of oxygen and hydrogen in water, the energy flow into the system was strengthened, allowing not only more stable macromolecules to be formed, but also a greater background complexity for generating, maintaining, and operating them. The nitrification process also adapted by adding new clusters to existing ones when the atmospheric oxygen content started to rise [15]. Similarly, throughout present-day metabolisms, the RNA World still exists, the new DNA World having been superimposed without destroying it first. As at the beginning of life, generation of energy still happens at the cell membrane from where ATP carries it inside into the cell. Here, an energy buffering ring became attached to an earlier phosphate string facilitating energy exchange [16]. Therefore, according to the backward compatibility principle at all levels, new layers of complexity are integrated with previous ones. After this, it will be difficult, if not impossible, to change the new system, or to disintegrate it, while keeping it working. Thus, systems grow more conservative, and operate according to the backward compatibility principle.

Overall, chemical environmental conditions changed, first some 3.75 billion years ago through the release of oxygen by photosynthesis, and then radically after ca. 2.5 billion years when volcanoes began to spew out different minerals, those from the thickening crust of the Earth instead of from its deeper metal-rich core [17]. Thus, the anaerobic environment turned aerobic, with the many consequences for life. The backward compatibility principle also requires that temperatures remain roughly the same [18]: the operation of the system depends on an uncountable number of very temperature-sensitive chemical interactions. Indeed, the average temperature on Earth has remained roughly the same over the almost four billion years since life's origin [18]; the loss of greenhouse gases over time compensated the increase in solar radiation [19]. Moreover, this temperature is such that macromolecules can exist: at higher temperatures, they are unstable; at lower ones, they cannot operate.

#### LIFE'S TEMPERATURE REGIME

Because of entropic decay, each molecule degrades at a specific rate. New ones are formed at a turnover rate that varies from a fraction of seconds to a couple of days. The central reference molecule of the cell, DNA, is no exception: it is maintained by an elaborate repair apparatus, although, as ageing shows, this too is not without fault. DNA, as well as macromolecules like carbohydrates, proteins, and ATP are polymerised by hydrogenation, and broken down by dehydrogenation, which implies that a continual hydrogen exchange is taking place. In ATP, for example, this happens at such a rate that the total weight of this very small molecule hydrogenating and dehydrogenating over one day equals the person's body weight. The same happens in uncountable molecules interacting in a cell. As energy is released in each reaction, the system would overheat. However, hydrogen exchange between molecules is for free due to quantum tunneling [20].

Hydrogen is not only both an electron donor and acceptor, but it is also the smallest atom, so small that it behaves both as a particle - matter - with a specific mass and as a probability density distribution of charge location - a wave - with a specific amplitude. When molecules get closer to each other than the width of the amplitude, it depends on chance on which side the hydrogen finds itself from one instance to the next. Thus, it gets transferred statistically, energetically for free, from one molecule to another. This is unique to hydrogen: the larger the mass of the atom, the smaller the amplitude. Under Earthly conditions, even deuterium and tritium, isotopes of hydrogen, are too large. This explains the central role of hydrogen in life's biochemistry and the importance of water to life [21,22].

#### CONCLUSION

The physical approach to the problem of the origin of life allows a reconstruction from first principles. These

principles concern the behavior and growth of systems, and the thermodynamics of entropic decay. The appropriateness of its reasoning can be checked by observed structures and processes in recent systems.

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