

A Deductive Approach to Biogenesis!

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Abstract

This article reviews the main arguments on the nature of the early startup of life. It first puts the biogenetical processes into a physical and systems-theoretical perspective. Biogenesis in this case would not be about the construction of individual molecules according to a chemical approach, but about building up an energetically self-sustaining, dynamically organized chemical system from scratch. Initially, this system would have separated out from generally operating physicochemical processes, gradually becoming more independent of them. As a system, it had to build up its structure stepwise, each stage being more complex and stable than the previous one, without, however, changing its basic structure too much; as long as the structure of a system stays intact, it still operates in the same way even if chemical constituents change. This property of a system became especially useful when the systems, which had already evolved and operated for some 1.3 billion years, had to adapt to new environmental conditions at the time of the Great Oxygen Event, the GOE, and some 2.5 billion years ago. As energy processing systems, their constituent molecules carry the energy and can as such be replaced by other, more efficient ones as soon as the system require, or as soon as external chemical conditions change. It is the energy flow that started up initially and that as kept running both uninterrupted and faster ever since, and it is the energy flow that shaped both the system's structure as well as that of its constituent molecules. For this flow to continue, the system kept changing chemically, but for this to happen the general physical conditions of the environment need to have remained more or less the same.

Keywords: Biogenesis; Thermodynamics; DNA; Amino acids

Introduction

This article approaches the biogenetic process differently: a chemical approach is usually chosen, whereas my emphasis is a physical one with an emphasis on thermodynamics. As any system, a biological system can be considered as a thermodynamically dissipating, dynamic structure. In any organization, the energy flow is of uppermost importance relative to its constituent components. In biological organizations organisms, the flow depends on molecules carrying the energy. Organisms take in energy, either as chemical energy, or as light energy in the form of solar radiation, process it internally in chemical reactions, dissipating it in a degraded form. Their chemical components are either energetically upgraded during a recycling process, or leave the system as waste. The energy cannot be upgraded, however, and must therefore be generated and expelled continually, a process which must have continued uninterrupted in one form or the other right from the system's beginning at about 3.8 Gyr ago up to the present. The course of this flow has become ever more complex, and its rate ever faster as new physicochemical principles, chemical components, and entire networks were added to the system, all the while keeping its initial, basic operation intact and running.

So far, the emphasis in biogenetic studies is usually on experimentally reconstructing the abiotic buildup of individual molecules from scratch, either assembled from locally existing organic molecules, or from molecules raining down from outer space onto the Earth's surface. The drawback of such a chemical approach is that the molecules so reconstructed are thought to remain self-contained, non-interactive, whereas, in order to produce new molecules themselves, and also to be able to interact functionally within the same setting, they would have to interact with other molecules right from the beginning. In fact, what we have to understand is how the system they are part of can generate these molecules itself. Understanding how a living system might have built up therefore requires a systems approach. The system must be able to generate its molecules itself, and make them operate functionally together within it. As system components, they are highly interdependent, which means that a system, once formed in a particular

way, cannot change its operational structure, although it retains the possibility of replacing its components, improving these, or of adding new ones. This property is known in computer science as the backward compatibility principle. Keep what is working. Extend, improve, and supplement it. But never change it. Any structural change disrupts its operation. For biogenetic analysis, this principle implies that some molecules or biochemical pathways and structures can still be found as chemical fossils from earlier, even the earliest, evolutionary times. Furthermore, as a second principle, the more interactions added to a system, and the more specific, complex and more sensitive to external conditions they become, the more stable and reliable the molecules and their interactions have to be to keep the system operating.

The energy flow through this structure shapes it, along with the set of its ever-changing constituent molecules, their nature, and operation. According to this reasoning, the first phases of life may have been constituted by chemical elements and molecules quite different from those found in organisms today. It is the basic, ancient structure of the system that stays and that has to be reconstructed and recovered in biogenetic analysis. The chemical approach, though, leaves the question open of how the dynamic structure of complex chemical cell mechanisms presently found would as such have originated, maintained, and have evolved in the far past.

Initially, the processes constituting such systems will have diverged and separated out from generally occurring processes, but still keep interacting with those in their surroundings. The way they could

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Received: October 29, 2014; **Accepted:** January 30, 2015; **Published:** January 06, 2015

Citation: Hengeveld R (2015) A Deductive Approach to Biogenesis! *Organic Chem Curr Res* 1:135. doi:[10.4172/2161-0401.1000135](http://dx.doi.org/10.4172/2161-0401.1000135)

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have separated out, diverged, and complexified forms the study of the origin of life. Yet, as we cannot know the first steps of this process of divergence from direct observations, the only methodological approach is to narrow down the various possible solutions. We have to show which processes can work, and which cannot. Then, by progressively excluding unlikely possibilities the one after the other, the likelihood grows of biogenesis having happened along the ways still left open.

Why Chemical Attempts at Biogenetic Reconstruction cannot Work

Traditionally, Charles Darwin was the first to have formulated the model of a warm little pond as life's cradle: in it, several chemical components, presumed to be essential to an initial biochemistry, should have combined such that a living structure came forth. The question remained whence these chemicals came, either from local resources or from some interstellar void. The persistence of such new, frail systems, though, requires calm, lukewarm water rather than the hot, turbulent water in or near black or white smokers. Also, when raining out of space, the compounds need to remain intact for a sufficiently long time to reach the proper concentration in a local pond in connection with the starting time of the biogenetic process. To form a self-sustaining, dynamic structure, moreover, they should also have been just the right chemical compounds, occurring in the right composition and concentration to form ever new compounds, either for continuing the system by reproducing it, or for its complexification. However, no individual molecule in a pond, whatever its origin, can be expected to occur in its proper biochemical context from scratch, or to have the right functional effect on other molecules. Furthermore, to keep the processes going, there should be a constant flow of these compounds from either local or from distant sources at a sufficient rate and concentration, and, moreover, for a sufficiently long duration before the system takes on their production. Without a continuous supply of new material and energy, all reactions soon reach their point of thermodynamic stability, so that the set of reactions dies an early death. Finally, no other compound should have been present or formed that could have disturbed the persistence and further development of the still frail system.

Amino acids, or formaldehyde - to highly complex ones - as proteins or DNA. Yet, any compound proposed, simple or complex can only operate and be maintained within a particular biochemical context; outside this context, they cannot exist. Also, most molecules mentioned are products of a long biochemical evolution towards a highly intricate, developed cell. Still, such compounds of widely varying complexity, operating only in highly evolved systems, are used as criteria to define life right from its earliest beginnings [1]. Typically, however, complex molecules such as some amino acid, a protein, or DNA only define life from that stage onwards at which they evolved. Such criteria for defining life should thus be avoided if we are to understand how life initially arose. Actually, defining life is still different from understanding it; based on circular reasoning, it in fact hampers our understanding [2].

Another problem concerns the kind of energy that makes reactants actually react, which varies from the benign warmth of Darwin's little pond, via violent electric discharges simulating lightning to mechanical shocks of heavy explosions [3]. But how could violent discharges or heavy explosions initiate and steer specifically operating, minute electrochemical energies. How could they initiate biochemical cycles, or determine the level of cellular homeostasis? And how could vibrational energy of the heat of Darwin's pond be converted into the electrochemical energy of biochemical reactions? Why not include

the chemo-thermodynamics of such reactions in our studies? In fact, whence the system's energy supply.

We have to study the origin and the development of a structure, of a system, of a cell, of a dynamic, energetically far-out-of-equilibrium system, rather than that of a single reactant or a set of them, which are, moreover, functionally independent of each other, apart from their energetics. That is, independent of the system's essential energy through flow. Systems, whatever their nature, exist by the flow of some form of energy. Moreover, we cannot predict the compounds needed within a biochemical context at a particular evolutionary stage from their local or astronomical availability. Nor can we predict the thermodynamics of a cell generating particular compounds or their recycling as long as this context remains missing [4,5]. The very impossibility of prediction explains why biogenetic reconstructions along these lines cannot work.

The real difficulty of solving the origin of the biochemistry of a cell and its energetics is that a model of the possible buildup of a system of interacting chemicals from its earliest beginnings is missing. This applies to both the underlying electrochemical energy flow, as well as to the phylogenetic sequence of interactions of the biochemical reactants. Also, it is arguable whether some biochemical model based on organic chemistry relates to the chemical evolution of the Earth's crust from which it is separating out. We only have a model of the way usable energy can have been generated [6]. But what exactly was the initial, pre-biological chemical system that separated out from of the crust; what was the geochemical constitution and evolution of the Earth's crust? How did the systems interact with the geochemistry of this crust, and how did these interactions co-evolve.

An Alternative Approach

Proposed an effective, simple mechanism that could have generated the energy needed under the earliest conditions [6]: as in a battery, a charge potential could have originated between the basic, oxidizing fluid inside a mineral crust of precipitate, and formed around a fine trickle from the basaltic sea floor into the reducing ocean water. The resulting charge disequilibrium could have maintained from the earliest, ancient times onward up to the present, allowing a constant energy flow to keep chemical processes running, first inside the initial precipitation crust and later within the membrane of subsequently evolving cells. As the environmental conditions of the ocean water turned from reducing to oxidising, this initial battery-like mechanism would have been substituted by the biological one of photosynthesis operating on solar energy. Yet, the initial, energy- processing mechanism within the cell, based on oxidation, remained intact as a system- bound, biochemical fossil.

Having thus solved the problem of the generation of energy, the problem that remained is how some energy-processing mechanism, increasingly diverging from other processes in the crust, may have originated, operated, and then, possibly as a response to radically changing environmental conditions, developed evolutionarily. Yet, because of the extreme complexity of a cell and its evolution, we will only be able to reconstruct the first steps of this evolution in detail. After these first steps, unknowable stochastic processes, partly due to processes of deterministic chaos in the by then multi-component systems, took over. Subsequent biological adaptation concerned various ways of keeping this stochasticity and its resulting biochemical instability within bounds.

However, subsequent studies by Russell and his group [7-9] diverted from his earlier deductive, thermodynamic approach of energy generation to an inductive chemical approach deriving results

from present-day biochemical processes. In the deductive approach, one can use present-day processes of energy generation as biochemical fossils for hypothesis testing, whereas in the inductive approach based on organic chemical processes; one cannot do this without falling into the trap of circular reasoning. Also, instead of the precipitation crusts growing as fine, linear tubes of iron monosulphide around individual trickles, like those generated in chemical gardens, Russell changed his model to clumps of cells tightly packed together. The fine tubes, though, leave room for a continuous flow of protons and electrons from the reducing seawater to the interior space, whereas the compacted cells, by sticking to each other, can hamper this flow. Also, Russell and his group assumed carbohydrates and simple nitrogen and phosphate compounds as precursors of the present organically-based biochemistry [7]. However, for the first stages, we need to formulate our questions in terms of inorganic chemistry rather than in those of organic chemistry [10-13] put the energy flow through the system central, comparing this flow with a water current that drives a waterwheel energizing processes within a mill, where the energy degrades. The mill itself can be repaired, partly or completely replaced, improved, or extended. Similarly, chemical elements and compounds within the initial systems could have been replaced according to changes in environmental conditions and to changes in the requirements of the dynamic stability of the processing system. Subsequent increases in this stability and the complexity of the system, will have increased the rate of energy through flow significantly.

However, in his considerations on the possible processes and phases of the evolutionary buildup of the biochemical system [14], looked mainly from the viewpoint of organic chemistry. For a bottom-up, deductive model of biogenesis, his thermodynamic and evolutionary approaches therefore need to be integrated with that of inorganic chemistry.

A Bio-Inorganic Beginning

proposed that a crust of iron and nickel monosulphides, FeS and NiS, may have precipitated between an oxidising space inside and a reducing environment outside [6]. This initial FeS crust can still be recognised in the ancient electron transferring FeS centers surrounded by increasingly longer evolving protein strands [15], known as ferredoxins. As biochemical fossils still found in bacteria, animals, and plants, these are operating as hydrogenases at low, reducing, redox potentials of -400mV.

Methodologically, such biochemical fossils therefore represent positive tests of the applicability of their deductive, physically mechanistic model of energy generation. The next step is to formulate some model of the processing of this energy after it has entered this tiny space. Without biological catalysts being available, compounds could only have been formed and broken down continuously by two elements that each donate and accept electrons easily [11]. This applies to selenium and hydrogen, which can also form chains of selenium hydrides of varying lengths. Such an easy bond formation and breakdown is conditional for energy processing within confined spaces lacking a significant material interchange with the environment, conditional for metabolic cycling, and thereby for chemical self-replication. Self-replication, in turn, speeds up the reaction rate of individual molecules and of more complex reaction cycles exponentially; it is in fact a pre-condition for enhancing metabolic rates [16]. Furthermore, by connecting an additional cycle to a first one, biological functionality originated, the first cycle being conditional to the next. Moreover, under reducing conditions, selenium can transfer hydrogen across membranes as hydrides [12]. Interestingly, instead of

Russell's sulphur, selenium also occurs in other ancient hydrogenases such as FeNiSe [17]: another candidate for the first crust. It should be noted that nickel was abundantly available particularly during the time life would have originated.

Like hydrogen, selenium has a relatively low electronegativity, which means that its electrons can easily be lost, as in metals, although, as said, that it can also accept them easily, as in non-metals. As this also means that its bonds are unstable relative to those of other non-metals, selenium could have been replaced by sulphur in the same elemental group but as it has stable bonds, it maintains the biochemistry of the system selenium had helped to form. Overall, such a replacement would have enhanced the stability of the molecules, and therefore the reliability of the specific reactions happening within the system. For systems-theoretical reasons, therefore, we can expect a tendency towards stability, which is also necessary within a fluctuating and changing environment. The strength of the bonds increases within the non-metals via sulphur and phosphorus in the direction of carbon, nitrogen and oxygen with relatively high electro-negativities at the right-hand top period of the Periodic System. Of these last three elements, carbon has the lowest electronegativity and therefore the weakest bonds, and oxygen on its right the highest with the strongest ones. The same trend is found among the halogens on the right of the non-metals, with fluorine at the top having, the highest electronegativity, and therefore the strongest and most stable bonds.

Having a strong bond means that the molecule is thermodynamically stable, which is why carbon forms stable materials, found in wood and starch, which should be durable. Similarly, proteins are polymerisations of amino acids, composed of nitrogen, carbon, and oxygen. These acids are polymerised by condensation to form all kinds of specific molecules from countless combinations of amino acids that remain themselves intact during protein hydrolysis. The same processes of condensation and hydrolysis also occur in carbohydrates and polyphosphates. Here, the relatively easy formation and breakage of the bonds within the oligophosphate chains facilitated by electron resonance from the ring structure of the base occurs functionally in nucleosides such as ATP, GTP, NAD, etc. These rings being folded back on the polyphosphate chain and connected by it by a divalent metal atom, magnesium, enhancing the resonance effect [18]. These nucleosides catalyse the formation of proteins with their stronger bonds, which, in turn, catalyse the formation of carbohydrates. Within the group of non-metals in the Periodic Table, selenium has the lowest electronegativity, sulphur a higher one, and oxygen at the top the highest of the three. As they occur in the same group, they exhibit similar chemical properties, although the stability of their bonds increases towards that of oxygen. This means that, with relatively minor adjustments in the structure of some compound or process, such elements can replace each other. We see this, for example, in the evolution of the older Photosystem I into the more recent Photosystem II where sulphur is replaced by oxygen. Sulphur may similarly have replaced selenium changing H₂Se into H₂S, a possible next step towards [14,19] early evolutionary Thio-World. During this stage, thioesters could have been involved in the synthesis of phospholipids and fatty acids by esterification. If so, the present-day phospholipid membrane would have originated sometime after, rather than at the very beginning of biogenesis as [20] suggested. Thioesters could also have formed the bonds between inorganic pyrophosphates which are precursors of AMP and other nucleosides [21] from the energetically equivalent bonds of thioesters. Those nucleosides, in turn, may have been implicated in the formation of the nucleic acids in RNA in the subsequent RNA World and, from this, in DNA of the present DNA World.

By fuelling reactions with electrons, ATP and other nucleosides probably acted as energy transducers, which could have become more specific in their enzymatic functioning when they polymerized, first into RNA and eventually into DNA. If so, there would be a smooth evolutionary transition between metabolism and replication by functional extension and specialization, rather than an independent origin that has led to the metabolism-or- replication-first controversy [22].

Interestingly, during the early days of biogenesis, apart from transition elements as vanadium and tungsten [23], ferrous iron, Fe^{2+} , may have delivered the electrons for thioester formation which handed them over in the subsequent phosphorylation, a process for further metabolic oxidations by electrons. Ferrous iron could have been reconstituted from ferric iron, Fe^{3+} , by energy obtained from UV light in the iron cycle [14]. According to de Duve, one can imagine that during the initial stages of biogenesis, ferrous iron may similarly have been involved as an electron source, and thus as a source of energy.

Because UV radiation does not penetrate deeply into water, this would mean that life originated in relatively shallow waters. Although UV radiation can penetrate to a depth of 50-70 meters in very clear water, this penetration reduces in opaque water to only 30 meters [24]. Moreover, dissolved silicon must have shielded early life forms completely off from UV radiation [25]. In oceans covered with ice and many kilometers deep, such as found on Jupiter's moon Europa, or in the soils of Mars, life cannot possibly originate and be maintained.

The supply of energy, even chemical energy, had its ultimate source in a continuous flow of electro-chemical energy from the environment. Without this flow, any reaction system would reach its thermodynamic point of stability before too long by sheer energy exhaustion. Later, when oxygen was produced in photosynthesis by cyanobacteria, the iron, bound in large quantities as Fe_2O_3 , became more difficult to obtain as a metabolic source of energy. In fact, the concentration of dissolved iron decreased by a factor of 45,000 [23]. Its energy-generating function was then replaced by oxygen, released as a waste product by the photosynthetic reduction of water, and the UV radiation therefore by less energy-rich solar radiation.

We therefore recognise a neat evolutionary development of metabolism, starting at the tip of the non-metals in the Periodic System, fanning out to the upper period of these elements. Transition Group metals, together with hydrogen, delivered electrons, starting at the left and gradually moving towards the right. Gradually, new elements were added, thereby often partially replacing older ones, supplying new biochemical functions according to their specific physicochemical properties. As new elements were added, they often - partially - replaced older ones. Biochemical development would thus broadly have followed the structure of the Periodic System, thus according to trends in the electronegativity of the elements concerned, basic to the chemothermodynamic properties of the biological systems.

Changing Environmental Conditions, and Structural Complexification

On the whole, therefore, the energetics of the earliest systems depends on a transfer of electrons and protons from a reducing environment outside the precipitation crust into an oxidising one inside [26], a process that has continued up to the present time. From early on, organisms are oxidising structures having gradually diverged from generally occurring, abiotic processes within a reducing sea. The result was, inevitably, a gradual depletion of the electron and proton sources.

Apart from this, the atmosphere also grew less reducing. Through the photo dissociation of water under the influence of UV radiation, the very light hydrogen escaped into space, after which the remaining oxygen built up and oxidised atmospheric methane, thereby forming carbon dioxide and water [27]. All three are greenhouse gases. This initially relatively slow oxidation process greatly speeded up during the Great Oxygenation Event about 2.5 Gyr ago. Before this period, the volcanoes threw up material from the metallic core under a still thin, solid crust covering the early Earth. Because of cooling of the planet, this crust grew thicker so that at some point the volcanoes did not reach the lower, electron-rich parts anymore. From then on, they drew their material from the more oxidised crust [28]. This caused the concentrations of, for example, nickel, cobalt, and magnesium to fall substantially, whereas those of sodium and potassium rose. Only during mid-Proterozoic times, other transition metals, such as copper and zinc became available [12].

The speeding up of the redox state of the environment happened during the same period from which the first oxygen-producing cyanobacteria have been recorded, the time when the Proterozoic Eon of their great blossoming (2,500-543 Myr) began. The anoxic oceans became slightly oxic at the surface, although remaining sulphidic below, whereas the partial pressure of atmospheric oxygen rose substantially [29]. The oxygenation of the oceans produced the insoluble Fe_2O_3 . The result was that, together with the insoluble Fe-sulphides at deeper layers, iron was lost from the water, becoming unavailable for life. Like iron, another redox-sensitive metal, molybdenum, was also removed from solution. Both elements are important for the fixation of dinitrogen, N_2 , into ammonium.

During this time of gradual oxidation of the atmosphere, the nitrogen cycle evolved, which meant that the processes of nitrification and denitrification oxidised the ammonium in the ocean. Under the early reducing conditions, ammonium in the oceans oxidised under more oxic conditions, first, to nitrite and then to nitrate under an increasingly higher oxidation state of the environment [30]. As the oxygen concentration rose, inorganic nitrogen, N_2 , ran short in the oceans, thereby threatening life's survival. Denitrification was one of the processes that reduced the further rise in concentration of free oxygen, O_2 [30,31]. All this also used up part of the oxygen produced, which could explain the gap of 300-500 million years between the appearance of cyanobacteria and the accumulation of oxygen in the atmosphere [32].

During that long period, the biochemistry and enzymology of organisms thus had to be adapted to the significantly changing redox environmental conditions by the superposition of entire, new metabolic reaction networks. This superposition will have taken place several times in various taxa independently; occurring only after the three kingdoms of the Eubacteria, Archaeobacteria, and Eukaryotes had diverged, and even had split up themselves into some phyla [33].

The fact that these various successive metabolic networks can still be recognised as three clusters means that they were superimposed on top of existing ones having been built in the past. As can be expected, the already existing ones kept operating as relatively independent modules constituting the metabolic system, the new ones not disturbing the system by rigorous reconstruction. It is not quite clear whether the three clusters of pathways and cycles of [33] coincide with those of de Duve.

The development of the biochemical Z-scheme could have been one of the other adaptations to a less reducing environment keeping the

energy flow running uninterruptedly [11]. As this system began at low, negative redox values comparable to those in the ancient environment, those in the environment had now shifted to high, positive ones. According to the backward-compatibility principle, the Z-scheme shows how, in a two-step process with added energy fed by the installation of both photosystems in succession and operating in series, the same, initially low redox values in the cytosol were maintained. Similarly, the initially high proton concentration of the reducing ocean turned to the low concentrations of an oxidising environment. The charge difference can be thought to have been maintained artificially by a novel biochemical mechanism, the proton-motive force, in which protons are first pumped out across the cell membrane and then in again [11].

Again and again, by adding mechanisms to already existing structures, complexity increased. First, the addition of the more ancient Photosystem I, which split H_2S , and then Photosystem II which splits the stronger bond of H_2O , required both the biochemistry and the genetics behind it to be extended and complexify. This idea holds because especially the strongly electronegative oxygen was released into the system by the reduction of water into oxygen radicals and H_2O_2 , potentially disrupting its operation. New cellular organization [13] and newly formed molecules had to undo their disrupting effects. Understandably, all such additions required the superposition of entire, greatly complexifying and, hence, very energy-demanding reaction networks on top of the existing ones.

This kind of complexification process occurred already from early on in primitive compounds. For example, at some point, the ancient iron sulphur molecules obtained four strings of primitive proteins that, possibly over time, were extended step-wise by attaching seven amino acids in succession [15]. Obviously, for this to happen, some generating and maintenance systems had to evolve and be implemented into the system. Even such a simple structural internal adaptation to external changing conditions will have developed into a more complex system.

The rate of complexification must have increased exponentially over time because many mutually dependent adaptations had to be implemented. The operation of the system as a whole may therefore have slowed down exponentially, unless the rates of the individual processes also increased exponentially. This happens to be true for auto-catalytic chemical replication processes [16]. Of course, this means that the supply and throughput of materials and energy must have increased equally. With respiration, the great amount of light energy needed for splitting water into hydrogen and oxygen later becomes available to the cell when hydrogen is oxidised back into water. This released energy thus feeds the complex, increasingly energy-hungry metabolic system. This, of course, could have required new, complexifying processes. By increasing the throughput, though, the chemical kinetic stability of the system increases at the expense of the thermodynamic stability, which decreases because the system is using up increasingly more energy [16].

As soon as an individual positive feedback process gets the upper hand, it disrupts and thereby destroys the system's operation. If not kept within bounds by some negative feedback process, [16] self-enhancing, auto-catalytic positive feedback reactions, though, would lead to chaos and disruption. Homeostatic processes, by dampening the fluctuations between the processes of rapid growth and subsequent collapse, regulate the unbounded growth of individual processes going astray within the system. This means that both the level and the bounds of fluctuation are set in negative-feedback reactions. This negative feedback system had itself to be generated and maintained by some other subsystem which, in turn, has to be kept within bounds, and so on. Of course, all these processes have to be laid down and regulated genetically as well. As

newcomers, they have to fit and operate within, or on top of, previously evolved, complex and ever more complexifying homeostatic, regulating network of negative feedback processes. The genetic regulation of all these processes standardised the interactions between molecules, but added yet another reaction network.

Moreover, if my model of the biochemical phylogeny following the trend in the Period System towards greater electronegativity among the non-metals holds true [2,11], the increasingly more stable compounds that constitute the system can only be formed catalytically by an elaborate set of biological enzymes, which are themselves formed and broken down enzymatically as well. This increase in bond stability thus enhances once again the tendency towards an exponentially greater system complexity. In fact, this tendency towards greater stability follows directly from the trend towards greater complexity just because, without all the regulating interconnections between an increasing number of processes, the system would become less reliable with the risk that it would eventually collapse. An increase in complexity necessitates an increase in stabilising measures to be taken, and *vice versa*. Their interconnectedness is a property of systems occurring in fluctuating or gradually changing environments.

This tendency towards increased stability requires both the input of increasing amounts of material and energy to keep the system in a far-from-equilibrium state, and of enhancing reaction rates between elements with increasingly stronger bonds. This explains [16] proposed tendency towards increasing dynamic kinetic stability of these systems at the expense of their thermodynamic stability: during their evolution, biological systems grow ever more energy demanding. This tendency accords with Boltzmann's Dream: the flow of energy tends to run ever faster.

Therefore, according to the principle of backward compatibility, the complexification and stabilisation of life resulted from a superposition, rather than a replacement, not only of individual compounds, but of entire reaction networks as a response to ever-changing environmental conditions. Life is a compartment of and within its surroundings without having the possibility of ever beginning again; it has to adjust and add adaptive structures continually in order to face the ever-changing, external conditions mused on what would have happened to life if the Earth had been larger.

Constant Environmental Conditions

Many environmental conditions changed dramatically during the time life built up on Earth, whereas other ones kept constant or changed very slowly. For example, under the influence of the Moon, the rate of axial rotation of the Earth slowed down gradually so that the days and nights grew longer. During the Archean, for example, both lasted for only 8 hours, while at the beginning of the Proterozoic Eon their duration had increased to 12.3 hours, which affects the amount of continuous solar radiation. Moreover, after having originated from the impact of a Mars-size planet with the Earth, the Moon itself gradually became more distant to the Earth and its rotation around it slower. This would have affected the turbulence of the ocean: initially, there will have been huge tidal waves at high frequencies, with a thorough mixing of water as a result.

Of the conditions that remained constant, I mention two, gravity as a result of the constant size of the Earth, and temperature, partly as a result of gravity, and partly as a result of several compensatory factors and negative feedback processes. Over time, due to accretion of material from cosmological impacts and dust, the size and, consequently, the

gravity of the Earth will have increased slightly. However, the impact of gravity on physicochemical processes may be considered as virtually constant [34], once gravity more significant. He felt that, for example, trees would not have grown as large as they do now [35], and that animals would move about more slowly [36]. It will also have affected their size and blood circulation, for example. Planetary size is also important in connection with the expected temperature range of the atmosphere: planets larger than Earth have a greater atmospheric density due to their larger gravity and are, as a consequence, warmer [37]. Conversely, smaller planets are expected to be colder.

At the molecular level, gravity would also have had an effect. The molecules would have been packed together tighter, making their interactions more intense. This would affect their chemical reactivity and the quantum tunneling of electrons and protons. Of these, quantum tunneling appears to be an exceedingly influential process in life's redox reactions. Quantum tunneling occurs when the distance between two molecules is smaller than the amplitude of the quantum-mechanical wave function of an electron or a proton. Then, there is a relatively high probability of such a particle simultaneously occurring on each side of the gap between two molecules. When this gap widens as a result of the thermal vibration of the molecules, the particle may find itself attached to the opposite molecule relative to where it was before. This explains a very easy hydrogen transition between molecules. It would not have cost any energy, which is of exceedingly great importance, given the huge number of reactions occurring between hydrogen and other molecules in metabolism. Even a slight increase in the size of a particle like a proton to that of deuterium, by adding one neutron to a proton, implies that the wave function of this particle is that much smaller than life cannot exist: it cannot bridge intermolecular gaps. Because the size and therefore the gravity of the Earth are constant, intermolecular distances must always have been the same, and quantum tunnelling significant.

However, if the initial temperatures had been higher, the vibrations of these molecules would have been greater, enhancing their reaction rates because of the greater frequency and intensity with which they bump against each other. On the other hand, they could also break apart more easily, which especially applies to macromolecules. Such molecules are stable at rather a narrow temperature range, whereas their interactions are highly sensitive to temperature. From systems-theoretical considerations, despite fluctuations in space and time, the temperature range should therefore have remained roughly constant right from the beginning of life at some level of complexity. The more interactions happening between the components of a system, the larger the molecules, the more intricate the dynamic of the system, and the more sensitive the specific interactions are to temperature, the more stable the temperature needs to be for the operation of the system to continue. An analysis of the size distribution of the pits 2.7 Gyr old, left by Proterozoic raindrops shows that at that time temperatures were similar to those of the present [38]. Petrochemical estimates show that temperatures from 3.5 Gyr onwards have also remained constant [39]; they were certainly less than 55°C, and probably fluctuated around 22°C (P. Vroon, pers. comm.). At that time, the expected strong greenhouse warming due to higher atmospheric methane and carbon dioxide concentrations compensated for the lower luminosity of the Sun. In addition, the temperature-dependent weathering of rock by atmospheric carbon dioxide formed a negative feedback system, which kept the temperatures constant [40,41].

The Probability of Planetary Habitability and the Occurrence of Extraterrestrial Life

For about four hundred years or more, one of the main interests in the study of biogenesis has been the idea that the Earth might not be the only habitable planet in the universe and that, as a consequence, life may also occur extra terrestrially. Some think that other planets or even that communication could be possible with human-like creatures in equally well-developed societies as our own. Drake's Equation [42,43] intends to express the probability of extraterrestrial life happening as a function of, for example, the number of stars in the universe with planets of the right size, circling at a proper distance around them. At present, an intense research interest has grown concerning the existence of exoplanets, planets around other stars than our Sun. However, so far, in particular very large planets have been found with, therefore, the greatest gravity, as these are the easiest to be observed. Moreover, as their gravity is very great, they circle round their star at high speed and close distance, and, because of the intensity of the radiation, are extremely hot, or they circle around two stars instead of one, etc. [44,45]. Yet other stars cooled off too" quickly for life to develop fully. Also, the location of a star with planets within its galaxy is of influence. Apart from this, Earth possessing a moon that originated from a unique collision with another planet early in its existence [46], with all the effects on living conditions, is unrepeatably [47]. In all these and other respects, Earth proves to take a very exceptional position, which makes Drake's initial estimations of the number of habitable planets from the sheer number of stars over-simplistic.

Drake's Equation derives the probability of life existing on exoplanets, not from the probability of the same biochemical mechanism repeating itself from the same elemental and chemical ingredients and by the same processes of evolution as proposed here, but by estimating the, so far unknown, number of planets that could have the same conditions as we have on Earth. So far, however, the probability of life occurring on any planet should be derived from the only planet with life, that is, from the Earth. Predicting its recurrence is therefore like an alien predicting the development of our climate from one single precipitation measurement. But even then, the Earth's climate appears immeasurably much simpler than life with its capricious evolutionary development over almost four billion years.

This equation does not include any biological factors and processes in sufficient detail, nor their evolution, let alone take into account the level and pattern of their temporal and spatial variation [42,48]. Neither does the equation contain detailed information about the evolution of geochemical conditions; the literature usually only mentions the availability of liquid water, or of atmospheric water vapour. The equation neglects the effect of the kind of radiation, its intensity and variation, or of the maximum water depth at which life can develop, etc.

It is also often thought to be possible that other forms of life exist based on other elements, such as silicon [49]. However, there is logic in its present composition and its development, life's evolution following the structure of the Periodic System. It cannot deviate from this. This composition depends on the unique geochemical origin and development of the Earth, also in connection with the timing and way some other planet of a particular size hit it, creating the Moon. Here, we have to look particularly at a thin upper layer of the Earth's crust as well as at various parameters of the seeping out of certain elements from it, and at other aspects of a planet's volcanic activity. The chemical composition, on which the development of a precipitation crust with a particular composition depends, as well as the composition of

the fluid in the space inside this crust, determines the probability of life originating and that of the same conditions and developmental processes being repeated exactly elsewhere.

Thus, the possibility of life originating somewhere else in the universe does not simply depend on the existence of water at the right temperature only. We need to know the physicochemical conditions peculiar for this to happen, the right quantitative elemental composition of the crust, as well as changes in geochemical and physicochemical living conditions within the context of a developing planet, this in relation to the further evolutionary, highly stochastic development of life over 3.8 billion years after its origination. The probability of these conditions ever being repeated exactly, especially to form other human-like creatures elsewhere with the same kind of societal, intellectual, and technological development [50] is infinitely small, if not incalculably small [51]. We can be certain that life on Earth is unique in the entire universe [42].

Conclusions

This paper concentrates on the type of questions being asked about the processes of biogenesis, putting the flow of energy central. This automatically shifts the general problem from a chemical one to one of thermodynamics and physical inorganic chemistry. It also implies that biogenesis does not concern the origin and evolution of individual chemical components, rather it concerns the splitting off of processes of intense interactions, which gradually diverge from those in the early oceans to form an increasingly more distinct system run by a flow of energy. As a consequence, it is a systems-theoretical approach in principle. Over evolutionary time, this system grew ever more complex and stable, starting with inorganic non-metal elements with low electronegativity, such as selenium and hydrogen, with weak bonds that easily form and break down, which were gradually replaced by elements with higher electronegativity, ending with elements with the strongest and, hence, the most stable bonds, carbon, nitrogen, and oxygen. Thus, these latter three elements, at present taking a central metabolic position, would have been the last ones to have been adopted instead of the first, as generally proposed. Their late inclusion into life processes is because their bond formation and breakdown requires an exceedingly elaborate set of complex enzymes, themselves requiring a reliable, stable subset of informational mechanisms and processes as well. DNA as an information carrying macromolecule can be conceived as a specialised, highly complex, and specifically responding enzyme, similar to the way ribosomes presently conceived as ribozymes [52]. It can have evolved from RNA, and therefore out of an initially nucleoside background. As such, RNA and DNA keep interacting homeostatically with intricate metabolic processes occurring in the cytosol [53].

As the system grew more complex, existing components, whether individual molecules, or entire biochemical structures or process systems, kept working within a changing biochemical environment, according to the systems-theoretical backward-compatibility principle. Similarly, subsystems evolved, continually adapting the system to changing external conditions, such that the general structure of the process, though extended and supplemented, kept intact. Thus, the present life systems are mixes of superimposed processes and process networks of very different ages. When one follows a methodologically deductive, bottom-up approach of analysis, the more ancient components, chemical fossils from quite different living conditions in the far geochemical past, can be used for testing hypothetical evolutionary models. All in all, the proposed analytical methodology can open up new perspectives for those studying life's origin.

Acknowledgement

I would like to thank Claire Hengeveld-Nicholls again for rigorously correcting the English. Our son Sytse made useful suggestions about systems theory. Once more, David Goodall corrected, and commented again on, a late stage of the development of this article.

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Citation: Hengeveld R (2015) A Deductive Approach to Biogenesis! Organic Chem Curr Res 1:135. doi:10.4172/2161-0401.1000135

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