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Origin of life — Symmetry breaking in the universe: Emergence of homochirality

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Abstract

Attempting to understand life's origin is finding a hypothetical sequence of physicochemical steps (based on distinct logical conditions) that lead to individuals with a life-like genetic apparatus. An oligomer emerges that is able to replicate. It must be homochiral to allow precise interlocking between template and growing replicate. Life evolves on the planet: symmetry breaking, emergence of homochirality.

Keywords: Origin of life; Chirality; Symmetry breaking; Molecular engineering; Self-organization

1. Introduction

The question of how life emerged has a number of different aspects that have been studied intensively in the past few years [1–4]. In one of these aspects chemical reactions have been studied that give information on what may have happened on the prebiotic planet that can be relevant to life's origin:

1) How chemical reactions on prebiotic earth might have led to precursors of biomolecules [5].
2) How replicating strands might have been arisen [6,7].
3) How the synthesis of various nucleic acids, e.g. pyranosyl-RNA, contribute in understanding early evolution [8,9••].
4) How self-organizing biochemical cycles may have developed [10].
5) How vesicles divide and multiply [11,12].
6) How early metabolism may have developed via thioester forming short polymers [13] or on two-dimensional surfaces of pyrite as autotropic origin [14,15].

In a further aspect theoretical concepts have been developed that are important in today's views on the origin of life:

1) The hypothesis that conditions to form self-organizing molecular systems in a homogeneous medium in a steady state far from equilibrium are essential in understanding the emergence of life [16] and profound investigation of principles of self-organization in that case [17••–20].
2) Double origin hypothesis: emergence of the genetic machinery within the pre-existing metabolic unit [21].
3) Hypothesis that life criteria are the presence of an individual unit, metabolism, inherent stability, information-carrying subsystem, regulated processes; potential life criteria are growth and reproduction. Minimal life: Chemoton [22].

The present paper has a different focus: Can we understand the emergence of life as a process based on physics and chemistry, i.e. can we find a distinct continuous sequence of hypothetical physicochemical steps finally leading to a bio-like genetic apparatus, the basic machinery of bio-systems? This means: can we identify, by logical considerations, the revolutionary changes in structure and functionality required to reach that goal; can we find why, by what mechanisms, these changes should occur, by what environmental influences they should be driven by chance and necessity.

Such questions lead to the particular paradigm of the present approach: First, attempt to find the logic pattern of a process

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that leads to a bio-like genetic apparatus: Try to find out by systematic thinking how that ingenious and complex machinery could have evolved in many distinct steps. Then, try to give a sequence of hypothetical steps that are based on this logic structure, on the existing chemistry and physics, and in accord with prebiotic conditions and biochemical requirements. Develop such a hypothesis to reach an increasingly reliable, realistic, detailed and experimentally supported description of the process.

Here we restrict to general aspects and give a more detailed description of only the very first hypothetical steps including the step leading to homochirality.

2. Essence of present approach

Living individuals, in the present context, are molecules or aggregates of distinctly interlocked molecules that can reproduce themselves in the given environment and evolve, as a form, in appropriate achievable environments into forms of continuously increasing complexity and functional intricacy. By what reason life emerged and evolved? Is its appearance the result of a physico-chemical process to be specified step for step?

2.1. Paradigm: search for a continuous sequence of physicochemical steps toward a life-like genetic apparatus

The requirement for living aggregates to come into being, resulting from logical considerations, should hold anywhere in the universe at appropriate locations; the chemistry can be similar to the one on the early earth, or quite different.

The question, can we model a detailed sequence of physicochemical steps that leads to individuals with a bio-like genetic apparatus, is also of principle nature. It is an attempt to answer the question: can the origin of life be understood on the basis of physics and chemistry, is it not in contradiction to thermodynamics?

A hypothetical pathway has been modeled [23••,24•–28•, 29,30•–34]. The intention was not to describe the historical pathway but to show that a reasonable pathway can actually be given (by specifying the fundamental changes in structure and functionality required to finally reach a life-like genetic apparatus, by showing that no barrier appears that is not surmountable).

Increasingly detailed theoretical modeling and efforts in experimental support would be most important to get closer to answer that fundamental question. But it is widely believed that the basic question has been answered in 1971 (called annus mirabilis [22]). The conditions of self-organization in the special case of a homogeneous phase in a steady state were studied [16] and Darwinian processes taking place under those conditions were profoundly investigated [17••–20]. The aim was finding principles of self-organization. This work of Manfred Eigen has strongly influenced and activated today's thinking on evolutionary processes. He developed, on that basis, an evolutionary biotechnology allowing to get proteins with entirely new functionalities that is of primary importance in future achievements.

Attempting to find how and why the protein-producing genetic machinery emerged requires a basically different approach proposed in 1972 and indicated above [23••]: trying to solve a distinct engineering problem, to find a pathway to a given goal, not principles of self-organization. Principle features become manifest in actually proceeding along such a pathway (Sections 3 and 7).

In searching for such a sequence of steps very particular environmental conditions had to be assumed as the driving force to reach the given goal: a distinct periodicity in time, compartmentalization and structural micro-diversity. From logical considerations discussed below, these boundary conditions appear as a general requirement in modeling the emergence of bio-systems. They are the basis to understand why and how life emerged.

In my opinion a basic assumption for life to begin is the presence of an extremely particular location where the conditions are given for the synthesis of monomers that are used as the building blocks of replicating oligomers. In the vicinity small regions are present with distinct, specific properties required to drive the self-engineering process finally leading to a genetic apparatus. The problem to be solved is a very specific engineering task, a priori in agreement with thermodynamics.

As mentioned it has been assumed that the condition for life to emerge is given by the condition for self-organization in a homogeneous phase in a steady state (to be far from equilibrium) [17••]. This is in contrast to what follows from the argumentation given above and specified in Section 3 that the complexity and distinctness of the environmental conditions is fundamental for driving the complex sequential processes leading to life's emergence.

2.2. Molecular engineering and life's origin

Seeing life's emergence as a distinct engineering process driven by most special environmental conditions, has developed from the idea that chemistry should have a new goal: the synthesis of different types of molecules, planned to interlock in a distinct manner, like the components of a machine. A machine is a functional unity designed for a given purpose.

This new topic was called "Molecular engineering" to emphasize that it is a counterpart of molecular biology. First attempts to realize molecular engineering was to construct simple prototypes of supramolecular machines and of molecular based electronic devices [35–37]. A most important step toward the aim of a molecular engineering was the invention of the scanning tunneling microscope and the atomic force microscope by Binning and Rohrer. Measuring the electric current through a single molecule of particular structure has been recently achieved [38]. It is an important step toward future molecular electronic devices. Molecular engineering (molecular electronics, nanotechnology, supramolecular chemistry initiated by Jean-Marie Lehn) is a strongly developing topic. The close relation between the search for ways to construct molecular devices and attempts to find the basic mechanisms in life's emergence should be seen as a useful guideline in future developments.

3. General conditions for life to come into being: periodicity in time, compartmentalization and structural diversity

We are looking for what is required, just from logical considerations, to stimulate a process leading to aggregates of

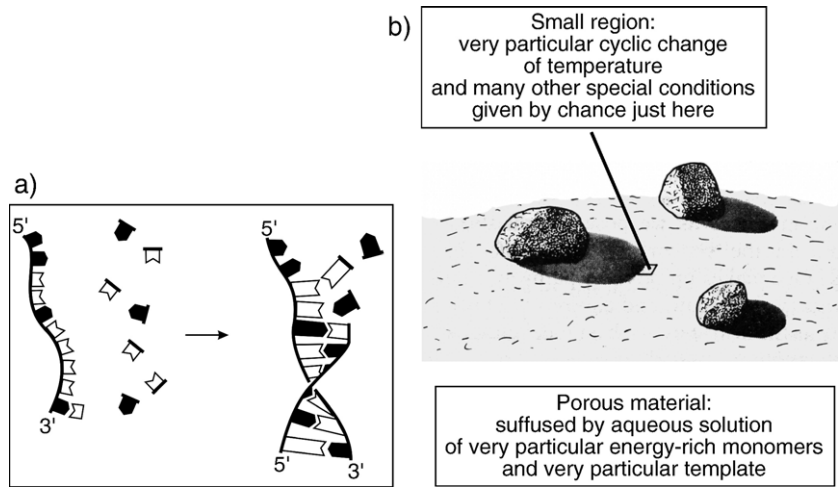

Fig. 1. Modeling emergence of first replicating strand (assuming the simplest hypothetical way) (a) in a very particular location on the prebiotic planet (b). It is assumed that the monomer orientation of template and growing replica are antiparallel as in bio-system where the replication begins at the 3′ end of the template and moves toward the 5′ end, while the replica grows in the 5′-3′ direction.

interlocking molecules evolving to systems of increasing complexity and intricacy.

A first condition is the presence of a molecule that is self-reproducing in the given environment, whereby variations (copies with a defect) can still replicate, e.g. an oligomer R (Fig. 1a). This requires energy-rich building blocks that can assemble forming complementary oligomers under particular conditions, and it requires a particular spatial structure and a distinct periodicity in time which imposes a cycle of repeated self-reproduction (multiplication) of molecules R, variation and selection. The extremely specific environmental conditions driving these first and later steps in the evolutionary process are assumed to be present in a very special location somewhere on the prebiotic earth, and anywhere else in the universe where corresponding conditions hold.

Further conditions to form aggregates of increasing functional intricacy must be given as follows:

(i) Periodicity: oligomers R must be induced to multiply and subsequently to aggregate in a very specific way. To be exposed to a selection process, to dissociate and then to be ready again to multiply, requires distinct environmental conditions. Basically different situations must follow each other, a most specific periodic change of conditions is needed to enable that particular process. For example, it may be driven by the day–night periodicity (Fig. 1b).

(ii) Compartmentalization: the single oligomers occurring in the multiplication phase should not be able to escape easily, otherwise no aggregates would be formed. The region must be compartmentalized (e.g. porous rock), keeping the oligomers together.

(iii) Microdiversity: microdiversity of the environment is the fundamental driving force to form entities that are more and more functionally sophisticated. Neighborhood regions with slightly different (less favorable) structural properties cannot be populated in the beginning but by casual occurrence of slightly improved forms. More and more complex forms evolve by colonizing further and further regions (Fig. 2). In this way difficulties in rationalizing the evolution toward increasing complexity can be avoided. Microdiversity serves as an evolutionary gradient.

The continuous extension of the populated area in the highly diversified world, beginning with oligomers R emerging at that very special location, is the basic mechanism leading to the origin of life. A continuous drive to increasing complexity is given by the necessity of increasing sophistication required to populate decreasingly favorable regions.

In my view the given conditions are fundamental requirements for the emergence of life in the universe, they are to be considered as postulates.

4. Particularity of physical objects defined as living individuals: carriers of information and knowledge

We can say that these molecular aggregates carry information, the recipe to produce copies of themselves, to carry this information to their descendents. Forms evolve of increasing quality of information, i.e. increasing knowledge (increasing know-how to survive, as a form, in increasingly complex surroundings). The emergence of life is the emergence of an

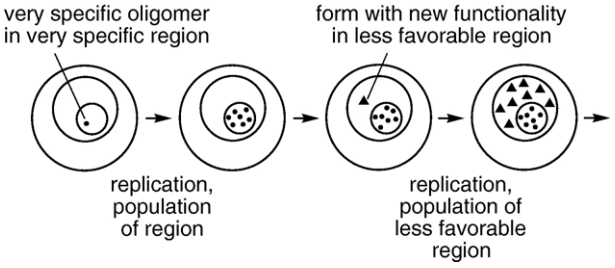

Fig. 2. Evolution of increasingly complex selfreproducing forms by populating increasingly unfavorable regions.

information-carrying and knowledge accumulating form of matter. Living individuals behave as if they have a purpose, an intention, an aim. This begins, all of a sudden. with the first object that evolves in a particular environment by multiplication, variation and selection. A fundamentally new property appears (not present in any ancestral form in the prebiotic world).

The emergence of life is widely seen as a process that takes place gradually. Whether this is true or not depends on how life is defined. Life, as defined in Section 2, has a beginning all of a sudden. There should be important template-assisted previous processes, but the emergence of the first carrier of information all over generations, is sudden. Its occurrence is a tiny bang in the universe. This should emphasize the fundamental nature of this initial event.

In the following we restrict ourselves to a closer look on the very first steps of that very long way toward a genetic apparatus.

5. Modeling pathway. The beginning: emergence of a short strand that is homochiral and has the power to replicate in the given very special environment

As mentioned above, attempts have been made to give a sequence of physico-chemical steps beginning with the first replicating strand and leading to a genetic apparatus and a genetic code of the kind given in nature. The time for each step has been estimated [23••]; the process can be fast compared to the time available on earth. In the following we restrict ourselves to the very first steps and to a short discussion of general features.

5.1. Engineering aspects

5.1.1. A short template marks the beginning

We consider a solution of two kinds of monomers (capable to bind by covalent links) that may assemble into short polymer strands. The two kinds of monomers are complementary. The first short polymer strand that is, by chance, structured in a most particular manner, serves as a template for the synthesis of further strands. Once the template strand has formed, monomers are attached because of their complementarity (e.g. by hydrogen bonding) and a double strand is considered to be formed (Fig. 1a). We suppose that an unusual event occurs to initiate the dawn of life, for instance, some environmental change occurs during drying and redissolving of a solution so that the first short template strand forms.

5.1.2. Intricate cycles of environmental conditions drive replication

Further essentials are e.g. distinct cyclical temperature changes that drive strand replication indicated in Fig. 1b by a small region exposed to the day-and-night cycle and a particular light and shadow change. A double strand which is formed at low temperature can be split into two single strands at high temperature (the weak hydrogen bonds break, but the strong covalent bonds persist); replication occurs when lowering the temperature. The arrangement of the monomers in the copy is complementary to that in the template strand (with regard to their lock-and-key properties)[1]. We assume that a spontaneously formed strand is only replicable in the given environment when a precise template-assisted interlocking to form a daughter strand is possible.

5.1.3. Homochirality of first template strand and replication

In the thought-experiment [23••,28•] the daughter strand grows by precisely binding an appropriate additional monomer that reaches, by diffusion, the growth position created by the template strand and the already existing portion of the daughter strand. The precision of the interlocking is a consequence of the strands being twisted. (Fig. 1a). Then, the monomers must be chiral and the template strand must consist of monomers of the same chirality, and this must also be the case for the monomers forming the daughter strand. Monomers of incorrect chirality are rejected.

Assuming that left-handed and right-handed monomers are present in equal amounts under prebiotic conditions it is equally probable that the strand that initiates an evolutionary process is left-handed or right-handed (frozen accident). In this view the fact that all life on earth is homochiral may be a consequence of a single molecular process. Then the emergence of life on earth is a break of symmetry to be compared with the breaks of symmetry in the evolution of the universe (e.g. the upheaval, by an accident, of a system containing neutrinos and neutrons into electrons and protons, while a transition into positrons and antiprotons would be a priori equally probable).

Life can have started at a number of locations on the early earth resulting, occasionally, in right handed, occasionally in left handed forms. They occasionally interacted, thereby one chiral form became stronger at the expense of the other one and finally one form survived in the struggle, resulting in the homochirality and in the uniformity of the genetic code on the planet.

5.2. Chemical aspects

5.2.1. Chemical nature of first template ready to evolve

Many different chemical conditions that might fulfill the engineering requirements should be kept in mind in considering life's origin on earth. Among the candidates for the monomers forming strand R are molecules similar to nucleotides forming ribonucleic acid (RNA), the nucleotides guanine (G), cytosine (C), adenine (A), and uracil (U). Our theoretical modeling (Figs. 1a and 4) is based on the hypothesis that the first template ready to evolve is composed of G and C. We favor G and C for the beginning, because they basepair with three rather than two hydrogen bonds allowing a more rigid niche at grow position.

Nucleotides are chiral because ribose, one of their components, is chiral, and nucleotides with D-ribose have opposite chirality from those containing the L-isomer. Nucleotides with the same chirality, either D or L, are considered to form the first template.

[1] The idea that distinct cyclic changes are a basic driving force in the origin of life is supported experimentally [7]. Replication and exponential amplification of DNA analogues is achieved by exposing templates to a periodically changing environment, allowing, in succession, complementary binding of oligomers at template strands, chemical ligation, and liberation of new strands from templates. Original templates and new strands, after liberation, are immobilized to avoid formation of stable duplexes. Cyclic repetition allows an exponential increase in the amount of strands.

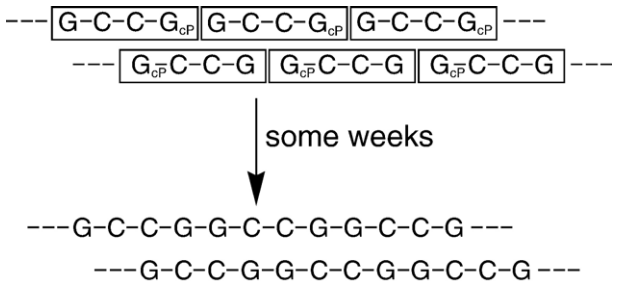

Fig. 3. Chiroselective self-assembly by oligomerization of homochiral tetramers of nucleotides.

Monomers of incorrect chirality are rejected in buildup of new daughter strands: They do not fit into the niche at the growth position (lock-and-key principle). Attempts to experimentally realize this kind of processes would be a great challenge.

The view of symmetry breaking by a frozen accident [23••] is supported by the important finding by Eschenmoser et al. [9••] that pyranosyl-RNA (which is a stronger and more selective pairing system than the natural furanosyl-RNA) is obtained in pure L or pure D form by oligomerization of G–C–C–GcP tetramers (where cP means cyclophosphate). These tetramers consist of D and L nucleotides linked at random (mixed D and L tetramers besides pure D and pure L tetramers). Alone pure D (or pure L) tetramers oligomerize by self-assembly (Fig. 3). Each tetramer carries cP that opens up by linking the phosphate group to the 4′ end of the adjacent tetramer. This reaction occurs under mild conditions and only in the presence of the template.

5.2.2. Prebiotic synthesis of building blocks required in the evolution of the genetic apparatus

It is a great challenge to find chemical possibilities showing how to reach the unique situation initiating the explosion of life and subsequent evolutionary stages. What biochemical compounds were available on the prebiotic earth? In classical prebiotic chemistry the starting material arose in "robust" reactions.

Very recently, Eschenmoser [39••] has given a hypothesis based on the idea that early biomolecules arose in non-robust organo-chemical reactions. One of the possible starting points is HCN. Its dimer and tetramer are hydrolysed such that glyoxylic acid dihydroxyfumaric acid (or their amides) are formed. The formation of dihydroxyfumaric acid can involve (hypothetical) autocatalytic cycles and act as the root of a reaction-tree that is leading to all important building blocks of biomolecules. Interestingly, the glyoxylic acid / dihydroxyfumaric acid can in principle be also reached from CO and/or CO2 by neutral and reductive oligomerization respectively. (A. Eschenmoser, private communication).

Distinct environmental properties must be given in particular compartments to build up and maintain each of these autocatalytic cycles. The conditions given in Section 3 govern the process. This means that prebiotic chemistry is based on the same basic conditions as the evolution of replicating oligomers toward the genetic apparatus. This is an exciting feature of Eschenmoser's approach. It is clearly hypothetical at this stage but it is a clear basis for experimental check. The properties initiating and driving each cycle will have to be specified, and showing how cycle-forming products may accumulate in appropriate compartments will have to be modeled.

6. Modeling pathway: emergence of first aggregates

6.1. Strand evolution requires rare replication errors

The arrangement of the monomers in the first template strand is determined by chance, so all of the copies have the same or the complementary accidental structure. During the replication process, however, errors can occur. Most of these errors are detrimental; by chance and very rarely, however, such an error imparts an advantage upon the replicate strand, improving its adaptation to environmental conditions (e.g. to the porous structure in rocky material, Fig. 1b), and its descendants eventually replace their less efficient fellow strands.

6.2. Strand lengthening — colonization of larger porous regions

We consider short strands which are well adapted to the fine pore structure in rocky material. By chance and under very special circumstances (e.g. partial drying and redissolution), two short strands can combine to make a longer one. What is important at this point is the presence of a neighboring region, suffused by monomers, with pores that offer almost – but not quite – adequate confinement for the existing short strands. The longer strands are then better adapted to the large pore size region, because they are constrained from being lost by diffusion; the populated area extends by the colonization of pores with larger openings by longer strands. However, replication errors set an upper limit for this process as well. It cannot be avoided that for longer strands the replication error probability is much larger than for the shorter ones, and we need mechanisms to eliminate error copies.

6.3. Strand folding: hairpins — most resistant structure

A long strand is exposed to chemical attack from the environment. How can the reactive groups along the strand be protected? A very effective possibility for the strand is to fold back onto itself to form weak bonds between complementary groups. The most favorable conformation is a complete fitting of all groups along the strand forming a perfect hairpin (Fig. 4a). The hairpin conformation requires an antiparallel monomer orientation (Fig. 1a). With monomers oriented parallel the formation of hairpins is impossible. The perfect replica of a hairpin is again a hairpin (Fig. 4a). A most significant aspect is that hairpins being homochiral have a helical twist causing rigidity important in forming aggregates of well interlocking components.

6.4. Aggregation of hairpins: an error filter

A strand folded into a hairpin is well protected against attacks from outside. This protection can easily improved by aggregation (picket-fence like structure (Fig. 4b); lateral binding of hairpins by e.g. counterions)). The aggregates are larger than single hairpins; hence they are able to colonize larger pores,

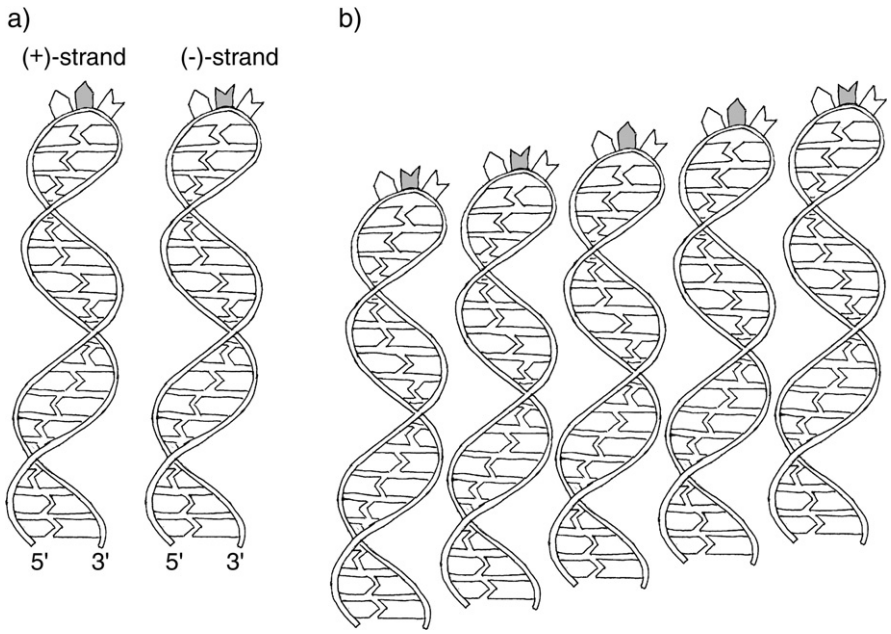

Fig. 4. Oligonucleotide forming hairpin and complementary replicate ((+) hairpin and (−) hairpin). Particular feature of hairpin: template and replica differ only in the monomers in the center of the strand (both gray, they are complementary) (a). Picket-fence like aggregate of hairpins, illustrating a simplest device that eliminates unfavorable copies obtained due to errors in replication. Hairpins laterally bound by e.g. counterions and possibly adsorbed at a surface) (b).

whereas single hairpins cannot. There is another advantage of aggregation: Erroneous copies of hairpins which do not fit into the aggregate will be eliminated.

On the other hand, errors that do not affect incorporation into the aggregate are not lethal; this means that further evolution of the strands can occur. An aggregate of hairpins can be designated as the first supramolecular machine. Its function is to select properly folded hairpins. We can say it preserves the know-how to make hairpins. It is the first form of life in the sense of being an entity that reproduces itself in the given environment and evolves, as a form, in appropriate achievable environments into forms of continuously increasing complexity and functional intricacy.

7. General aspects of life's emergence and evolution

Evolving increasingly complex forms requires increasing genetic information and accordingly smaller error probability P (the error probability P must be small enough to preserve the accumulated information (N bits), but large enough to produce variations by occasional copying errors, i.e. its optimum value should roughly be given by $PN=1$ [23••]. A situation is reached, again and again, where the presently available copying device cannot be used anymore. A fundamental change of the genetic apparatus must have taken place allowing to copy with each time smaller error probability P. The first basic change, in the hypothetical model, was the emergence of the hairpins–aggregation–error filter. In many equally fundamental hypothetical changes evolved the present-day genetic apparatus. Its limitation is the unavoidability of copying errors by thermal motion This limit is reached probably in the human and higher animal genome (for an estimate see [23••]). The appearance of artificial information storing and processing systems should be seen as the fundamental revolutionary step to overcome this limit. I think the Internet plays a basic role in this expected break-through process.

7.1. Computer and bio-system

A computer is a device for processing information. Rolf Landauer [40] has described a digital computer, in principle, as a system of switches; each switch is represented by a particle in a modulated potential, changing periodically, thus driving the switch through a switching phase, a storage phase and a reset phase (Fig. 5). In the switching phase the switch is set by the directing field of other switches that are in the storage phase. Accordingly, in its storage phase the switch directs other switches that are in the switching phase. In the reset phase the switch is made ready for its use in the next period. Each switch, in the storage phase, is said to carry one bit of information.

It is fascinating to see that this mechanism is equally basic to bio-systems where each switch is represented by a

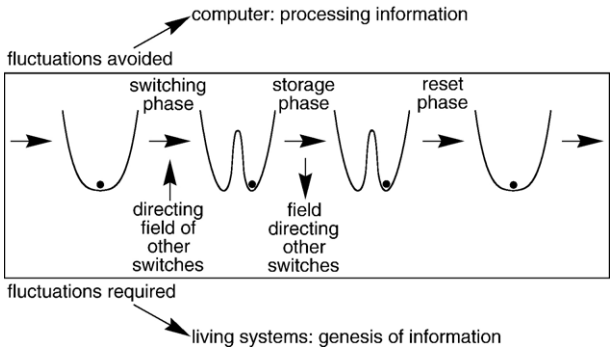

Fig. 5. Digital computer and bio-system.

complementary pair of nucleotides. For simplicity we assume that only one pair, e.g. G and C, is present in the DNA strand. The replication process represents the switching phase. The switch is set by the directing field of the template strand, i.e. the field of the hydrogen bond forming groups. This field determines which of the two complementary nucleotides is incorporated in the growing daughter strand. In the storage phase the considered nucleotide, now incorporated in a template strand, directs further processing. The decomposition of the strand into monomers represents the reset phase [29] (Fig. 5).

In spite of this accordance, a fundamental difference exists between the computer and the living system. In the computer the probability of a copying error (particle jumping from the one into the other minimum by thermal noise) is so small that the probability of an error during the complete computation is still very small. In the living system the error rate, as mentioned, is optimal to evolve.

7.2. Information I and knowledge K measured in bits

Some principle aspects of life's origin are elucidated by defining quantities that measure information and knowledge. Genetic information is stored and transferred from one generation to the next as a distinct sequence of monomers. This genetic information I is measured in bits increasing with the number of these monomers. How can we measure the quality, the actual value, of the genetically transferred information? It increases in the course of evolution. Thus, let us define Knowledge K of a given evolutionary stage as the total genetic information (measured in bits) that has to be discarded, in the average, by eliminating unfit individuals [24•,28•].

Beginning with a situation in which the emergence of a first replicating strand is possible it takes a huge number of trials (i.e. discarding much information) until a replicable strand actually appears (K growing suddenly from zero to a value given by the sum of discarded bits. Then K will slightly increase (reflecting refinements of the given structure and functionality) until a major change in structure and functionality appears (strong increase of K) (Fig. 6). This stepwise increase of K will go on and on. The process is analogous to what happens in the development of scientific theories according to Thomas Kuhn [41] (phases of normal science and scientific revolutions: changes in paradigm).

7.3. Entropy and knowledge

In my opinion, as mentioned in Section 2, thermodynamics does not play another role in the origin of life than in any other physicochemical process.

However, there is a similarity between the laws of thermodynamics (requirements for macro-physical processes to be possible) and the requirements for the emergence and evolution of life to be possible (Section 3).

There is a similarity between entropy of matter (being zero at $T=0$ and increasing with temperature) and knowledge (being zero before life begins (i.e. before the first replicable molecule appears) and increasing with time) [36]. Entropy increases suddenly at phase changes. Knowledge increases suddenly at revolutionary changes of structure and functionality (Fig. 6).

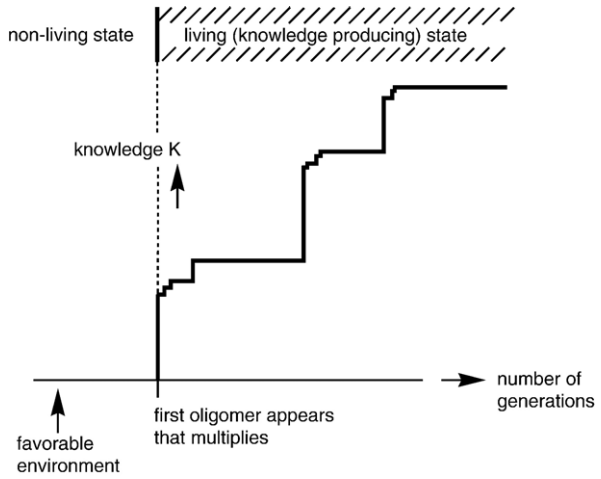

Fig. 6. Knowledge K of a given evolutionary stage (defined as total number of bits of genetic information required to be eliminated in the course of evolution) versus number of generations.

A thermodynamic state corresponds to an evolutionary stage. Entropy is given by the number of representations of the body in its thermodynamic state. Knowledge is given by the number of bits to be discarded by throwing away carriers of genetic information during the process leading to an evolutionary stage considered.

8. Conclusion

In my opinion the first goal to be approached in answering the question "What is life" is finding out, by logical considerations and on the basis of physics and chemistry, why and how a machinery like life's genetic apparatus can emerge in a stochastic process. This way to go leads to the view that the basic organizational structure of the machinery emerges by necessity when appropriate prebiotic conditions are given. Matter appears that has a fundamentally new property as compared to inanimate matter: to carry information and to accumulate knowledge.

According to the given model an RNA-like replication machine developed and evolved into an RNA-protein device that turned into a DNA–RNA–protein system required to overcome an evolutionary barrier at a distinct degree of complexity [23••,28•,30•]. A model has been given to explain why the genetic code is as it is [30•].

Here we considered only the very first steps. At some location a very particular prebiotic chemistry allows the occurrence of appropriate monomers, and the formation of oligomers. Occasionally, a strand appears that consists of monomers of the same chirality, appropriately linked. This strand serves as template for replication. This first casual event determines the chirality of all descendents. Thus in the model a break of symmetry has taken place on earth that determined the chirality of all life on the planet. The homochirality of amino acids is considered to be a consequence of the homochirality of nucleotides.

Life is defined in many different ways, e.g. [22]. In the present context we identified the emergence of life with the

occurrence of a molecule that has the power to replicate in the given environment and, as a form, to evolve. Matter (this molecule) comes into being that carries information, is homochiral and has the power to accumulate knowledge in a subsequent evolutionary process. The molecule has the basic properties that distinguish animate from inanimate.

"I think today's strong activity in developing chemistry relevant in life's origin (1-15) searching in many different directions is most significant. But the search for causes why and how life emerged should also be seen as an important task. The given pathway leading to a genetic apparatus should be further developed to become as realistic as possible. Results should be used as guideline for future experimental work. Actually giving such a hypothetical pathway (a sequence of steps based on physics and chemistry leading to a life-like genetic apparatus) - instead of just assuming that such a pathway can be given - is of basic relevance. Life's origin, in my opinion, is based on a theory, it is not a blind trial and error process."

A concerned chemist does not publish new ideas before having a convincing experimental support. This way to go should be changed when focusing on life's origin. Any new idea contributing to a hypothetical pathway can be a step further in understanding the process. We should listen to Linus Pauling. He said when being asked what do you recommend to young chemists? "I have astonished myself by moving into new fields. Part of the reason perhaps is, that I have developed early a feeling of confidence in my own intelligence This is very important to a young scientist. Don't rely just on what you read in the books! Think for yourself! Develop this confidence in yourself. Go ahead and be bold! Try out something new" [42].

I think there are similarities in attempts to describe the origin of life and the origin of the universe. Steven Weinberg says in his famous book [43] "Our mistake is not that we take our theories on the origin of the universe too seriously, but that we do not take them seriously enough".

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