Origin of life and physics: Diversified microstructure—Inducement to form Information-Carrying and Knowledge-Accumulating systems

by Hans Kuhn

The process leading to the origin and evolution of life is caused by the presence of distinct physical and chemical conditions at a distinct location in the universe. A specified system originates and evolves under the continuous influence of a complex operational environment. The system develops toward increasing independence of the original environment by becoming increasingly complex. Modeling a detailed scenario consisting of a sequence of reasonable physico-chemical steps is essential in rationalizing the phenomenon. The basic process, accumulation of knowledge by continuously testing environmental properties, is intimately related to the measuring process in physics. Evolution is a physical process, and this process leads to man developing physics. Thus physics appears to be self-consistent—the basis and consequence of evolution. The physics-producing system is considered to be a measuring and information-processing device based upon the mechanism which operates in the origin and evolution of life.

1. Landauer's modulated potential computer and the evolutionary process

I first met Rolf Landauer at a German Physics Society meeting in 1971 when he was lecturing on the modulated

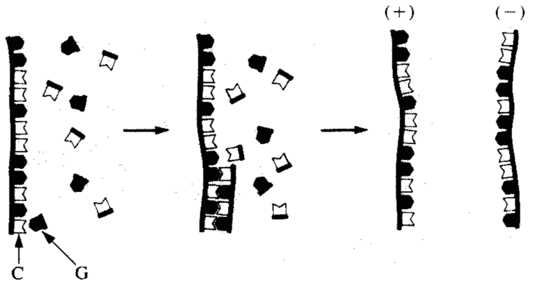


Figure 1

Replication and separation of (+) and (−) strands.

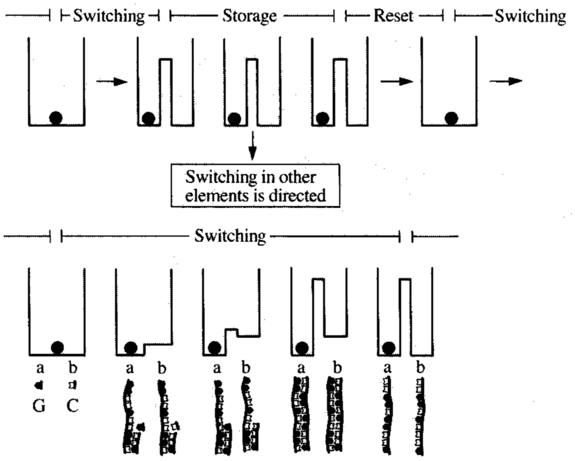


Figure 2

Model for computer and evolving system: case a—fit monomer G incorporated; case b—unfit monomer C incorporated.

potential computer. He presented a system of switches where each switch is changed in an externally driven process to pass through three phases—switching, storage, and reset. In the switching phase the switch is placed into a definite state by the influence of other switches that are in the storage phase. This is reached by changing a single-minimum to a double-minimum potential. In the storage phase the state of the switch under consideration remains fixed, and it influences other switches that are in the switching phase, thereby directing the course of the computation. In the reset phase the switch is returned to the original state (by changing the double-minimum to a single-minimum potential) [1].

I was very much excited by Landauer's lecture, since I had just developed a model of the origin of life based on the idea that the evolutionary process is governed by external cycles (such as the day-night change) driving the molecular system to pass through different phases [2]. Landauer's lecture made it very clear that there were parallels between evolutionary and computer processes. To see these striking parallels, we may consider a short strand obtained by joining monomers. It is assumed to be composed of two kinds of monomers complementary to each other, called G and C. In the given environment the strand has the ability to replicate; i.e., monomers attached to the strand in a sequence complementary to the sequence in this strand join, forming a complementary strand (see **Figure 1**). The complementary strand again serves as a template to form a copy of the original strand. Occasionally an error occurs in the replication process, resulting in a change in sequence. The environment is assumed to change properties such that a strand and a complementary strand replicate separately, forming folded conformations by intramolecular base pairing according to their sequences. These conformations may or may not survive this phase and enter into the next period where they can again replicate. The probability for survival depends on conformation, and the molecules with the sequences corresponding to the most appropriate conformations will be selected in this manner within a number of periods.

The two states of the switch in the modulated potential computer are analogous to the two kinds of monomers, G and C. The switching phase is the phase in which the monomer, under the directing field of the template strand, is inserted into the strand (see **Figure 2**). This field determines which one of the two kinds of monomers will be fixed (which is obviously the monomer complementary to the corresponding monomer in the template). The storage phase is reached when the newly formed strand is separated from the template strand. The monomer under consideration, now part of the new strand, directs the joining of monomers into strands of the next generation. The reset phase is the phase in which the monomer has become part of the strand that is discarded and degraded; the free monomer thus is regenerated and can be used again in the building up of new strands [3].

Landauer had shown [1] that the switching process can approach thermodynamic reversibility if the buildup of the double-minimum potential (while it is in the directing field of other switches) is made sufficiently slow. This is paralleled by the influence of the template in the evolutionary model. Assume that the template contains C at the location considered. When the complementary monomer G approaches this location, the potential energy is lower than during a similar approach of monomer C. The better the monomer fits into the niche in which it becomes bonded to the new strand, the better it is stabilized; and the larger the energy of this potential-energy step, the larger the barrier against interchange of monomers. The barrier is again considerably increased as polymerization proceeds. The process can be considered as approaching thermodynamic reversibility.

There is an important difference between the modulated potential computer and the evolutionary process. The operations in the computer being deterministic, the precision of the switching process must be large enough so that there is only a small probability of error in the entire computing process. In contrast, the evolutionary model must contain an indeterministic ingredient. There exists an optimal value of the probability of incorporating the monomer that is complementary to the corresponding monomer in the template. On the one hand, the probability that no error is made during strand replication must be large enough so that a sufficient number of error-free copies is available. On the other hand, as many mutants as possible must be generated to make the probability of finding an advantageous form among them as large as possible.

Therefore, with increasing strand length (increasing complexity of the evolving system), the required precision in incorporating the correct monomer increases. The basic difficulty in modeling the origin of life is finding a mechanism for the emergence of a device which allows replication with increasing precision for copying increasingly complex systems.

I attempted to approach this problem by trying first to understand the general aspects of the process, to develop an organizational framework of logic steps, and to trace a special scenario within that framework, a proposed sequence of many small, chemically and physico-chemically reasonable steps [2].

2. Emergence of Information-Carrying and Knowledge-Accumulating systems

The transition from a prebiotic situation on the planet—the coming and going of simple and more complex molecules in a complex, periodically changing environment—to first forms with some properties of living systems must be considered as a sudden process.

With the first self-reproducing and self-improving system (the first strand with the ability to replicate, occurring in a periodically changing environment that allows continuous multiplication of strands and selection), a meaningful message is transferred from one generation to the next: a code to self-organize a device for copying this same code (in the given environment that drives that process). This message constitutes information given by the number of bits carried by the self-reproducing system. This number is given by the number of monomers in the replicating strand, if only two kinds of monomer (G and C) are assumed to be present.

This process is restricted to a very special environment. Less appropriate regions cannot be populated. Slightly more complex systems occasionally appear through errors in the copying process or through other incidents by which the carrier of information is changed (such as the formation of a longer strand by condensation of two short strands). Sometimes such a system can survive and multiply in a less appropriate neighboring region, which then becomes populated. By this mechanism more and more sophisticated machinery develops; to populate a less appropriate region requires more complex machinery but offers a great selectional advantage to systems possessing such machinery. Such systems can develop in this region without being disturbed by competitors. Thus an evolution of increasingly more complex systems that populate increasingly unfavorable regions takes place.

With the more complex system, the value of the carried information has increased. The genetic message has gained in quality. This quality constitutes knowledge, where "knowledge" is measured by the total number of bits to be discarded by throwing away carriers of information, until the evolutionary stage under consideration is reached. "Knowledge" accumulates in the course of this evolutionary process. This term is helpful in realizing the fundamental nature of the sudden transition from nonliving systems to systems that have a basic property of living systems, i.e., the ability to carry information and to possess and gain "knowledge." As mentioned, this transition occurs with the emergence of the first self-reproducing and self-improving system. This point should be emphasized, since the origin of life is usually considered to be a vague, hazy change.

In this view the fundamental process leading to early life is a step-by-step liberation from the highly specific conditions first present, coupled with an evolution of increasingly complex systems, an increase in genetic information, and an increase in populated space. This process leads again and again to barriers. With the increase in genetic information the copying machinery repeatedly becomes too simple, and each time the question of how new machinery can emerge occurs in a scenario of the process.

3. Origin of life—A tricky engineering problem: How can diversified microstructure induce the formation of intricate machinery?

The general situation on a prebiotic planet can be considered as being given, and possible conditions at particular locations can be estimated. Within this framework we may search for appropriate conditions that drive the emergence and evolution of Information-Carrying and Knowledge-Accumulating systems. The problem of the origin of life is then a kind of engineering problem. Reasonable conditions are constructed, and the evolutionary process then taking place is estimated, aiming at a scenario consisting of a detailed sequence of concrete, experimentally testable steps.

Such a scenario is not intended to give the historic evolutionary path, but to indicate logical requirements and possibilities of realization. The basic problem then is to invent reasonable scenarios, i.e., to find possible conditions leading to relevant reaction sequences.

Important conditions for such a scenario are the following:

1. A steady source of free energy (the presence of energy-rich monomers in sufficient concentration in aqueous solution to allow for formation of polymers; this means that conditions must be given where the accumulation of molecules takes place by drying, re-dissolving, chromatographic separation, etc.).
2. A specific spatial and temporal structure.
   - The temperature should be oscillatory in time to drive a continuous change between conditions favorable to multiplication and to selection, respectively.
   - The environment should be porous and compartmentalized (i) to allow smaller molecules (acting as building blocks and energy carriers) to get in and out, (ii) to keep together cooperating larger molecules, and (iii) to keep off competitors.
   - The surrounding region should be diversified in order to drive evolution toward increasing complexity.

These conditions are assumed to be given at some particular point on the primeval planet, at a location where occasionally, among the ample variety of oscillatory time regimes and micro-environments, the situation is appropriate for many components to act together in the skillful manner necessary for the emergence of a self-reproducing and self-improving machinery. (An impressive example of a complex system emerging from a very specific environmental structure present at a particular location is the prehistoric natural nuclear reactor of Oklo [4]. Several conditions had to be fulfilled for the operation of the reactor: a very high concentration of uranium, a moderator for neutrons, and a specific concentration of neutron-absorbing material.)

4. Present approach versus popular view of origin of life being an innate property of homogeneous systems

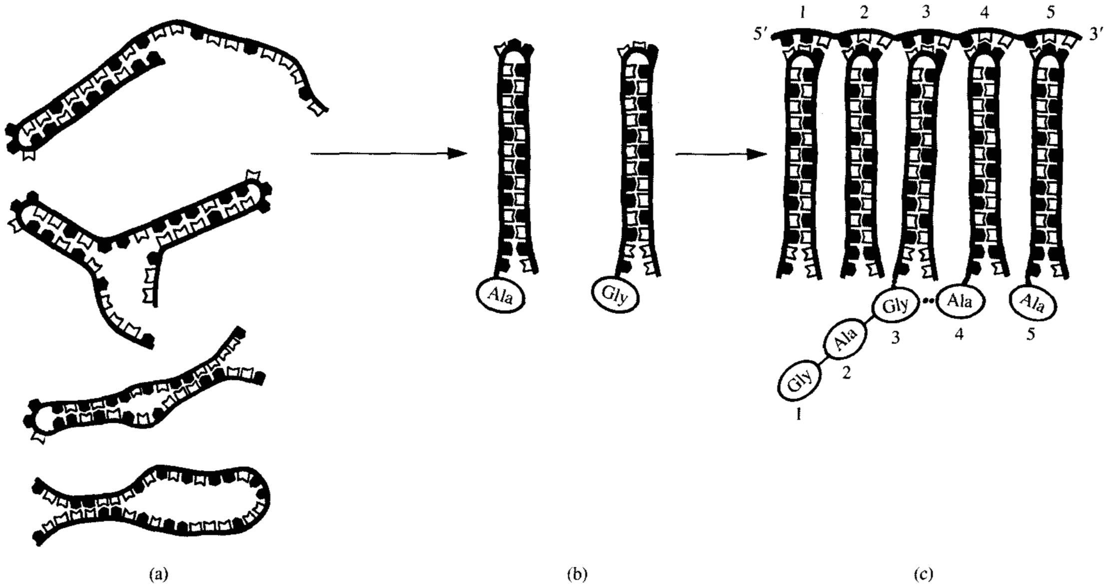
Two very popular assumptions in considerations of the origin of life are rejected in the present approach: the view that life emerged by self-organization of matter in an essentially homogeneous phase (an ocean of primeval soup) and the view that the process is a fundamental problem in thermodynamics. Both views are based on the idea that the process leads to the origin of life by intrinsic necessity, while in the present view the crucial point is, on the contrary, that this fundamental process is due to a very particular physico-chemical situation in a very particular operating environment present here and there in the universe. The origin of life on earth being restricted to a few small spots with highly particular conditions, quite unusual chemical and physico-chemical conditions can be assumed, and modeling the origin of life should be guided primarily by physico-chemical and chemical criteria rather than by views on general conditions on the prebiotic planet. This basic conception is supported by the recent most successful attempt by Eschenmoser et al. [5] to obtain very particular biochemically relevant compounds under oxygen-free and water-free conditions.

In 1971 many people saw the origin of life—taking place in the primeval soup—as an enigma in thermodynamics. I thought that the reason for the difficulty was the neglect of structural aspects, and that the difficulty would disappear if a very specific and highly structured time-dependent environment were assumed in which the system develops in many small steps, each arising in response to this environment. Because each step is in agreement with the known facts and laws of chemistry and physics, the particularity of the evolutionary process, in my opinion, should not be perceived on the plane of thermodynamics. It seemed to me important for the chemistry student to see that point by performing a computer experiment in which replication of strands (with a given error rate), selection, and evolution (by applying an external stimulus moving the system periodically between multiplication and selection phases) were simulated. This computer experiment, which we introduced (in the late sixties) in the laboratory course in physical chemistry at the University of Marburg, allowed the students to find the optimum replication error rate and to estimate the time required to evolve a system with the information content of a bacterium (see [6]). The importance of periodic heating and cooling as the driving force of repeated replication had already been recognized by Blum [7] in 1961. (I am grateful to Rolf Landauer, who recently called my attention to that paper.)

In contrast, Prigogine and Glansdorff [8] (who had studied the thermodynamic conditions underlying the formation of dissipative structures in a homogeneous medium in a stationary state) considered the origin of life (similar to the emergence of a Bénard [8] structure that does not occur before a critical temperature gradient is reached) as an intrinsic structure formation based on a new thermodynamic principle. Eigen considered the Prigogine–Glansdorff principle as fundamental, and as closing the gap between physics and biology [9]. His approach [10], also published in 1971, was based on the view that the fundamental phenomenon of self-organization, including the development of hypercycles, is a process that can occur in a homogeneous system by intrinsic necessity.

The difficulty in an approach based on the idea of intrinsic structure formation is to answer the question of how a system can spontaneously be formed that is sophisticated enough to develop into ever more complex forms. Eigen's approach presupposed a translation machinery forming an enzyme from a code given by the sequence of a nucleic acid strand. Eigen assumed that two or more such enzyme-producing systems cooperate by intrinsic necessity and that they form a reaction cycle (the hypercycle). With this concept he attempted to solve the basic problem of any evolutionary model: to overcome the noise barrier, the crucial evolutionary barrier caused by the increasing difficulty of obtaining a sufficient pool of error-free copies as the complexity increases.

In contrast, in my opinion the essential question to be answered was how to rationalize the emergence of a translation apparatus



(a) (b) (c)

Figure 3

Emergence of translation apparatus: (a) Nucleic acid strand conformations. (b) Amino acids Gly and Ala bound to 3′ end of (+) and (−) hairpin, respectively. (c) Aggregate of hairpins and collector strand. Hairpins bound to collector strand by complementary base pairing. Formation of oligopeptide with sequence related to sequence in collector strand.

forming enzymes from a code given by a nucleic acid sequence. Then hypercyclic interaction of forms equipped with a translation apparatus had no advantage (while at later stages in evolution the cooperation between cyclic reactions forming a superseded cycle is known and important, and the study of their mathematical structure useful [10]). The simplest primeval form of a translation apparatus seemed already so sophisticated that it could not have been formed by intrinsic necessity; it appeared obvious that a mechanism to overcome the noise barrier must have developed before the emergence of a translation apparatus, and that finding such a mechanism, and a mechanism leading to a primitive translation apparatus, should be seen as a fundamental problem.

It is of interest to mention that in Boltzmann's view the transition from inanimate to animate matter was compatible with the laws of physics and chemistry and was no puzzle in thermodynamics. "Boltzmann was not disquieted about what may now be called Prigogine's problem" [11]. Boltzmann, a strong supporter of Darwin, apparently realized that autocatalysis, diversification, and selection are the basic principles in the formation of purposefully acting systems. He mentioned in a lecture on the second law of thermodynamics, "We make the hypothesis that complexes of atoms evolved that could multiply by formation of similar complexes around themselves. Among the larger masses so formed those were most vital that could proliferate by division, further those that tended to move to places with favorable conditions for life."

5. Formation of aggregate: Key in surmounting noise barrier and in developing early translation apparatus

An important point in the detailed scenario given for the process [2, 12, 13] is the emergence of nucleic acid strands forming "hairpins" by intramolecular pairing of complementary bases (see **Figure 3**). They form aggregates by binding the bases in the hairpin loop to an open strand and by laterally binding the hairpins. Error-free copies interlock, forming the aggregate, while flawed copies are discarded. By this mechanism the noise barrier is surmounted. The systems evolve toward a translation device in which the open strand is the carrier of genetic information and the hairpins, binding amino acid, are the adaptors. In the aggregate of open nucleic acid strand and hairpins, the amino acids bind to one another in a sequence reflecting the sequence of the monomers in the open strand.

The process is supported by a computer simulation based on force field calculations [14]. Attempts were made to realize experimentally the proposed translation apparatus; the first steps (binding the hairpin loop by a triplet of complementary base pairs to an open nucleic acid strand) were successful [15, 16].

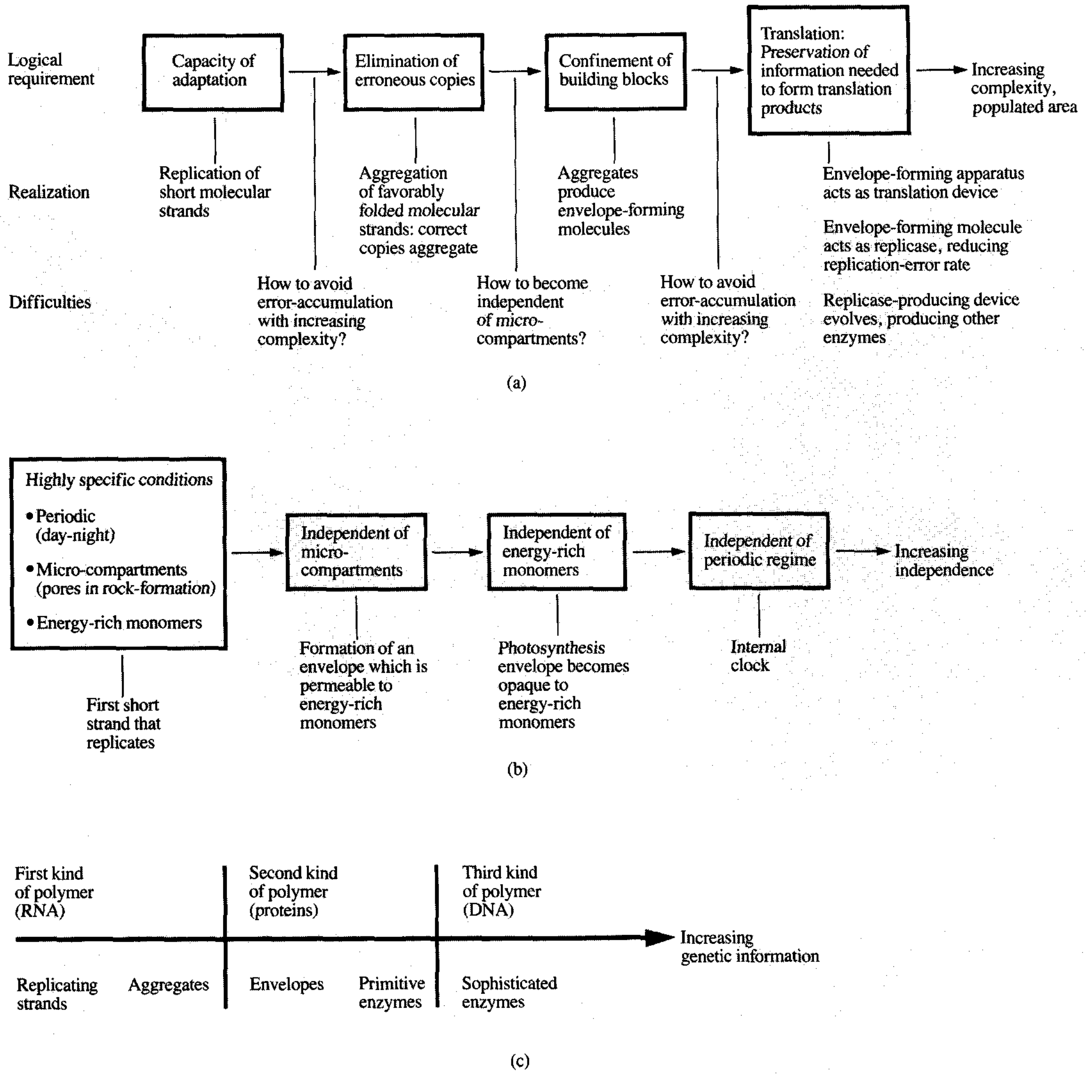


Figure 4

Organizational structure of evolution of early life: (a) Logical requirements, their realization, and barriers to overcome. (b) Major steps to reduced dependence. (c) Major steps in the development of the information-processing device.

6. Logical structure of the evolutionary process—Emergence of Knowledge-Accumulating systems: A fundamental phenomenon in physics

In the present view the evolutionary process, starting at a location with highly specific conditions, takes place as a development toward increasing independence, coupled with increasing populated space, increasing complexity, and increasing genetic information. The logical structure of the process can be seen in three ways. We can consider (1) the logic requirements, their realization, and the barriers to be overcome; (2) the major steps toward increasing independence; and (3) the major steps in the development of the information-processing device (**Figure 4**).

The importance of the process as a fundamental phenomenon in physics should be emphasized. It is basically different from simple noise-induced optimization processes. A global optimization strategy (many-times-repeated multiplication, occasional mutation and selection) leads to particular, far remote regions in configuration space. In the present view (different from the view of the origin of life being a process of intrinsic necessity), the entire evolutionary process is a consequence of the very particular interaction of the evolving system with the complex operating environment that is available. The process starts suddenly with the emergence of the first Knowledge-Accumulating systems (while in the view that self-organization is an innate process, the transition is gradual; the development of systems that respond to structural features occurs gradually at later stages).

7. Landauer's self-consistency between algorithms representing a physical law and physical executability of algorithms; the Wheeler meaning circuit and the emergence of Knowledge-Accumulating systems

The origin and evolution of life should be seen in the light of Rolf Landauer's thinking expressed in his lecture in 1971 and in recent papers on computation and physics [17–20]. In his search for the ultimate physical limitations of computing, Landauer realized the importance of the fact that computation is a physical process, restricted by the laws of physics and by the construction materials and operating environments available in our actual universe. Landauer emphasized that physical laws, in turn, consist of algorithms for information processing and must be consistent with the restrictions of the physical executability of algorithms, which in turn is dependent on physical laws. Landauer was much concerned with the question of what constitutes a measurement and what constitutes a set of measurements leading to a physical law. His view differs from that of Wheeler [21]. Wheeler's "meaning circuit" stresses the human observers and their posing of questions ("communication between communicators gives meaning"). In Landauer's opinion it is not clear that a set of measurements leading to a physical law "has to involve complex organisms that publish conference papers" and that Wheeler's meaning circuit does not close at a much lower level than in Wheeler's view.

I agree with Landauer, but tend to be more explicit. In my opinion Wheeler's "meaning circuit" can close with the appearance of the first self-reproducing and self-improving system. It carries a meaningful message from one generation to the next, which develops by continuously cycling between multiplication and selection phases, each time interacting with the environment. The systems building up according to this message possess the know-how to react upon influences of the existing environment in such a way that they have a good chance to survive the selection phase: They are constructed so that they follow an algorithm for information processing that leads to a behavior favorable for survival. This know-how improves with progressing evolution. The intricacy of the evolving system grows, and the physical limitations in information processing extend accordingly, consistent with the restrictions of physical executability. The meaning circuit extends accordingly in the course of evolution until it reaches the stage of human observers and their posing of questions. Thus, the physics-producing process is intimately related to the process leading to the origin and evolution of life, and its analysis is significant in the foundation of physics. This is discussed in Section 10.

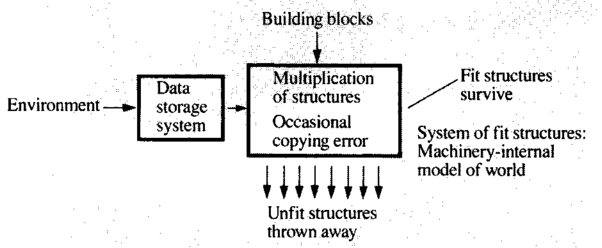


Figure 5

Model-observer: Knowledge-Accumulating device.

8. Observer—A Knowledge-Accumulating physical system

It seems of interest to discuss Landauer's question of what constitutes a set of measurements leading to a physical law by considering a simple model proposed in [22] to simulate the role of an intelligent observer (**Figure 5**). It consists of a device to observe, a device to store the observational data, and machinery for ordering these data by a process based on the principle of evolutionary processes: The machinery produces structures according to some rule given by its construction, and it selects the structure which is, by chance, better adapted to the stored observational data than all others. This structure is copied many times with casual copying errors. The copy which gives the best fit to the stored data is selected, and this process is repeated many times. The stored observational data are then erased and the memory space is used for storing new observational data. By the same mechanism, a number of such structures are replaced by a superseded structure, again saving memory space. The process, repeated at several levels, leads to a system of structures that fit the sum of the observational data that were transiently stored during the lifetime of the apparatus. This system of structures can be considered to be the machinery-internal model of the world. The number of bits to be thrown away in the process of building up that state (the "knowledge" gained) is limited by the construction of the machinery.

The basic process in the model-observer is not different from the basic process in evolution: Testing the suitability of a structure in the model-observer (by comparing it with the stored observational data or—in the case of a structure of higher hierarchic order—by comparing with structures of lower order) corresponds to testing the suitability of an individual in evolution (by exposing the individual to the given environment); discarding the structure in the model-observer corresponds to discarding the individual in evolution.

The observer model should indicate the importance of "knowledge"-producing mechanisms for natural and artificial intelligence and creativity.

The mechanism of "knowledge" production in the brain is not known, but it is known that signals from sensory inputs are multiplied and processed in parallel, interacting with many different parts of the cortex in different ways, and that a selection process takes place [23]. Evidence of many-times-repeated multiplication, selection, and recombination as the Knowledge-Accumulating process would be important. (The proposed mechanism is assumed to have emerged at a much earlier stage of evolution, when the first pattern recognition by individuals took place, and to have gradually evolved, leading to intelligent behavior. The principle of Darwinian selection operating on networks to form repertoires of recognizing elements, arranged in parallel and interconnected to categorize at higher hierarchic levels, was recently used to build a pattern-recognizing computer model [24].)

The logical sequence in the evolution of the increasing complexity of living systems [Figure 4(a)] should be relevant for the sequence of processes in the brain and should be a guideline in the search for basic mechanisms of creativity and intelligent behavior. Recombination appears as necessary to overcome a distinct barrier in the evolution of life (occurring later than the barriers indicated in Figure 4(a); see [13, Figures 17.16 and 17.17]). By the same logical requirement, recombination should occur with necessity if the amount of processed information reaches a certain value. It seems important to follow the basically transparent example of bio-evolution in future developments of natural and artificial creativity and intelligence, since the ingenuity apparent in biophysical mechanisms is comparable to the ingenuity of human ideas.

Can these considerations assist in attempting to answer Landauer's question: "How to define a measurement?" What constitutes a set of measurements leading to a physical law?

The model observer receives observational data (signals resulting from physical interactions of a measuring device with the environment) which are then stored and processed, thus adding to the knowledge of the observer. The signals from a set of measurements can lead to physical law. Knowledge-Accumulation then is an ultimate part of a measuring process which leads to a physical law. Knowledge-Accumulation, beginning with the origin of life and taking place in the human brain and in human society, contributes to the production of physics.

Landauer [20] and Bennett [25] have analyzed the actual measuring event and have clarified the problem of the minimum energy requirement. Before, inadequate arguments had been given which were widely and uncritically accepted. Landauer and Bennett realized that the inevitable minimal dissipation arises only when the information is discarded in order to reset the measuring device. Their argumentation resulted from a consideration of the Maxwell demon [25]. The demon receives information, acts accordingly, and erases the information to be ready for the next act; and only in the last step, resetting the instrument, is energy dissipation inevitable.

Is the coupling of the actual measuring event with the Knowledge-Producing system necessary for the process to constitute a measurement? Is the whistle of a steam cooker or the burst of a geyser a measurement? If someone responds meaningfully, it is a measurement. What is it otherwise? A rock at the edge of a river is a device to measure the water level, but not before somebody decides to use it for that purpose. Is what the Maxwell demon does a measurement? The information of the actual measuring event is discarded in resetting and not registered, in contrast to any stage in evolution, where the result of the interaction of the individual with the environment is registered by yes or no: to survive or not to survive the selection phase.

The present view that a measurement should only be considered as a measurement when the result is evaluated, i.e., when it is registered by a Knowledge-Accumulating system, and when it contributes to a gain in knowledge, should be clearly distinguished from Wigner's view (see [20]) that an observation is only an observation when it becomes part of the consciousness of the observer. The Knowledge-Accumulating system is considered to be a physical system, and within the context of a physical system the concept of consciousness has no meaning: The physical system is the object experienced by the conscious subject.

In Bohr's view the observation of an atomic phenomenon is based on a device capable of an "irreversible act of amplification." This act brings the measuring process "to close": One person is able to describe the recorded result of a measurement to another "in plain language" [26]. In the present view the Knowledge-Producing information-processing system (operating in the realm of classical physics) is considered to substitute for the human observer, and the act that brings the measuring process "to close" is the decision between survival and elimination of a structure. The irreversible act (where energy dissipation is inevitable) is the process of resetting (see Section 1 and Figure 2).

The concepts of information and knowledge are related to the concept of measurement. In the narrow sense information is the message transferred from somebody acting as the sender to somebody acting as the receiver, while in the present context information and knowledge measure a quality of matter that becomes manifest with the emergence of the first self-reproducing and self-improving systems. The genetic information is transferred from members of any given generation acting as senders to members of the next generation acting as receivers.

9. Evolutionary background of physics

As illustrated by the observer model of Section 8, the basic process leading to systems that form an internal model of the world is not confined to man, but the evolution of physics in its own right is intimately connected with the evolution of man. In order to survive, our predecessors had to develop a rational device to locate objects in a spatial and temporal range that allowed them to catch food. A three-dimensional internal model of the world is the simplest way to achieve this, and it seems reasonable that corresponding forms evolved. The operational environment was complex (a necessity for such a system to have evolved; see Section 3), and this intrinsic complexity prevents finding qualified rules comparable with physical laws.

A fundamental change took place only after man and human culture developed. An extreme simplification occurred with human language. Complex sensory patterns were re-coded by words such as "tree." The internal model of the world became an interplay of objects existing independently of actual situations. The fundamental importance of language in the emergence of individuals seeing themselves in an objective world should be emphasized [23]. At this stage an internal model of a world of objects was present. These objects behaved rather unpredictably, and finding simple, predictable phenomena was important. The restriction to simple arrangements that could be influenced and studied purposely was crucial for the emergence of physics. Sets of measurements were constituted that led to physical laws, and Wheeler's "communications between communicators" then became important in finding meaning in a superior sense, i.e., developing increasingly general concepts superseding special physical laws. This important step [comparable with earlier important breakthrough events (Figure 4)] occurred under particular conditions presupposed by man's curiosity, man's abilities to speak and to use his hands, and by a particular stage in the evolution of human society.

The data processing, at this stage, is not confined to the brain of the human observer. It takes place in human society beginning with the publication of conference papers by the observers. From many papers, some are selected, by acquiring more recognition from the scientific community than others. The ideas given in these papers interact and compete in many ways, and this process of multiplication, mutation, selection, and recombination is repeated many times. Textbooks appear and compete; what survives in this long Knowledge-Producing process is the physics of the time. Thus the "observer," the Knowledge-Producing physical system, is the body of many generations of scientific communities that participate in this evolution process.

Basically important was the appearance of artificial information-recording and -processing systems (written language, graphic representation, print, computer). The fundamental change in the mechanism of the evolutionary process with the emergence of artificial information storage systems in human society should be emphasized: Bioevolution is based on a molecular information-storage device restricting the amount of genetically transferred information to an upper limit given by thermal fluctuations [2, 12, 13]. Social evolution based on artificial information storage is not bound by this restriction.

10. Physics—Basis and consequence of evolution

In the preceding sections we have discussed the evolution of life and physics in terms of classical (non-relativistic) physics. (Assuming chemical bonding as a given, the essential molecular events can be described in the realm of classical physics.) The considerations lead to a presumed self-consistency in the sense that classical physics evolved as an internal model of the world; i.e., what was primarily considered as physical laws is presumed to reappear, constituting the internal model of the world.

In a fundamental sense this self-consistency means the following: The world is as it is—no physical laws exist. The laws of classical physics evolved, under given constraints in a narrow range in the universe, as the scheme ordering observational data to which human beings and their predecessors were exposed. This scheme appears as self-consistent, describing the construction and evolution of the information-processing system that leads to the scheme.

What do we expect if this classical information-processing system is supplied with observational data that cannot be described in the classical framework?

Fundamentally new schemes to describe these data will evolve, and again more new schemes will arise as physics develops further, similar to bio-evolution, where fundamentally new mechanisms develop with the step-by-step population of regions with entirely new constraints. It should be noted that the physics-producing information-processing system in which the evolution of the new schemes to rationalize observational data takes place operates unchanged in the realm of classical physics.

This should be considered in discussing interpretations of quantum mechanics where consciousness of the observer has played a crucial role. As Landauer [20] pointed out, "Some of the greatest figures in the development of quantum mechanics present us with almost mystical beliefs."

Quantum-mechanical wave functions exist in this classical information-processing system, exist in textbooks and as structures evolving in the brain of their reader; and the debate whether quantum-mechanical wave functions are "mathematical representations of knowledge" (Copenhagen interpretation) or "real waves physically present in space" (transactional interpretation [27]) does not seem to be meaningful.

The structure of our present physical laws is related to the structure of the human brain, and this structure is adequate to our immediate environment. Because we live in a three-dimensional world changing from past to future, and have difficulties in accepting features of nonlocality and relativity, an adequately constructed artificial "observer" using an information-processing device not necessarily based on classical physics may be more appropriate for rationalizing observational data originating from remote areas.

The author's intention has been to indicate that the process leading to the origin and evolution of life should be considered as a fundamental physical phenomenon. Physics appears to be self-consistent—the basis and consequence of evolution.

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Received May 21, 1987; accepted for publication August 18, 1987

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