Autogenesis:
On the Self-Organization of Life

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INTRODUCTORY REMARKS

It is rather awkward to comment on one's own contribution, even in this age of enhanced self-reference. It should be noted, however, that the following paper is an attempt for an *intuitive* synthesis of what the author has learned from studying autopoiesis, hypercycles, and dissipative structures, as they bear on the theme of the origins of life. Nothing more is being claimed. A short abstract follows.

An alternative view of the emergence of "living" systems and a special concept of "life" itself are being advanced. In this conception of life, uniformitarian in its premises and holistic by its design, the cell is considered to be the primary organizational entity capable of "life." This orientation includes both procaryotes and eucaryotes, as well as organelles. By "cell" we mean a protocell (or a protobiont), the first autopoietic unity.

It is the autopoiesis – the cyclical and unity-maintaining organization of even the simplest components – that may lead to the initial auto-organization of life, or autogenesis. Earlier experiments of synthetic biologists, coupled with Lamarckian respect for the environment and a proper dose of modern biochemistry, provide the necessary empirical framework for postulating the relatively rapid emergence of living phenomena and forms.

The emergence of a protocell cannot be separated from the variety of igneous rocks evolved and crystallized some 4 billion years ago. These primal crystalline formations, still uneroded and highly compartmentalized, exposed to the unceasing tidal rhythms of primeval oceans, became the cradles of life. In their innermost compartments, the biomatrices, the archaic nuclei and membranes developed their simple and elegant catalyzing interaction, fully protected in their womblike milieu from the harsh and tempestuous environment of the prebiotic seas.

By means of absorption and adsorption of primordial monomers, under the favorable thermodynamic conditions of the vast tidal zones, their structures were gradually transformed from predominantly inorganicmolecular to mostly organic-polymeric.

Subsequent erosive, volcanic, and mechanical events released the already complex protocells from their biomatrices in rich varieties of local forms and functional distinctions. Continually they spilled out into the waters and started on their parallel, predifferentiated evolutionary paths.

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INTRODUCTION

The question of the origin of life, possibly the greatest biological question, cannot be discussed yet outside the realm of conjecture and speculation. Not many biological scientists are willing to trod such doubtful and onrespected ground. Yet, it seems obvious that humans should keep asking questions about the origins of life and updating their conjectures. The essential incompleteness of scientific theories will always demand that their closure, however imperfect, be attempted.

This paper, written by a nonbiologist, is a simple presentation of several conjectures, possibly novel in character, that could point to fruitful directions for further research. They are meant as nothing more and the author will not take offense at being accused of simplicity.

Before discussing an origin of any kind, one must address some philosophical arguments against the possibility of spontaneous generation (i.e., life arising "by itself") (Farley 1977). These are exemplified by such Virchowian statements as "life is produced by life," "*omnis cellula e cellula*," "*omnis organisatio ex organisatione*," and other derived varieties of this theme. These considerations invoke the need for a preceding creator, a program, or at least an inner "language" to trigger the initial description-interpretation process.

One simple argument against *generatio de novo* could go as follows. For anything to produce itself is to act; if it acted before it was, it was then something and nothing at the same time. It acted before it brought itself into being. How could it act (process) without a being (state), unless it was? Nothing can act before it is. If something were the cause of itself, it must be before itself; it was before it was: *omne systema e systema*. | The precursor system must provide a "program" | 92 for the succeeding system.

The problem with this " reasoning" is that its presupposition, that the origin of a system is conceivable only through another system, and not as an outcome of certain *favorable conditions* occurring in the space of potential components, amounts to *denying* that the organization of a system must have "nonorganization" as its precursor; it then leads inevitably to the *belief* in special creation.[1]

In a solution of molecular components certain conditions (density, temperature, mixture, etc.) can arise such that the molecules concatenate themselves into particular spatial relations, forming a crystal. It would be difficult to argue that such a crystalline concatenation is due to random encounters: it emerges *whenever* the conditions are satisfied. A system, in this case allopoietic, arises from a "nonsystem" – an unordered solution of molecules. (Anyone who has experienced the stunning phenomenon of a sea "freezing over," the tremendous crystallization

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1 George Wald (1954) cautioned: "It is a symptom of the philosophical poverty of our... **[REST UNREADABLE]**."

of waters within minutes of the occurrence of proper temperature conditions, can confirm the compelling unavoidability of such a phenomenon.)

The question arises, can an autopoietic system, which is not defined simply as a spatial organization of components but as a circular concatenation of component-producing processes, similarly emerge under certain favorable conditions characterizing the environment of its components? Can life be compared with a particular type of "crystallization" of matter in the sense of being bound to appear when conditions are right?

Several comments should be made with respect to this question. First, some components must exist before the autopoietic unity does; that is, their ç processes are not yet a privy to the autopoietic system but are inherent in the molecular interactions in the physical space. The component-producing processes must exist by virtue of the existence of their products ; what does not exist is the particular organization necessary for their autopoiesis. Accordingly, autopoiesis may arise in a molecular system if the relations of production become concatenated in such a way that their products specify the system existing only while it is actively being produced by such a concatenation of processes (Maturana and Varela 1973).

Second, the actual (favorable) conditions existing on preautopoietic Earth are not necessarily deducible from the *presently* observable modes of existence of autopoietic systems. That is, organic macromolecules, nucleic acids, protein systems, and the like are the components of already *evolved* autopoietic systems, not necessarily of protoautopoietic systems. Such conditions might not exist anymore and even the possibility of their laboratory reconstruction could be debatable.

Third, the phenomenon of life cannot be fully predicted or explained from the quantum mechanics or chemistry of the molecular components. One can use the analogy with waves or waterfalls (i.e., dissipative structures). If life can be compared to a standing wave, a whirlpool, or a waterfall, then a detailed knowledge of the molecules taking part in its autopoiesis is not sufficient to explain it as a phenomenon. It is the *relations* among molecule-producing processes that are of primary interest.

Finally, there is the question of graduality, or continuity of nonlife and life. It is often alleged that a system either is or is not autopoietic (Maturana and Varela 1973). Intermediate steps are excluded and the natural extension of this idea is that anything could be either living or nonliving. Some sort of "vital principle," an autopoietic organization of life "snapping" itself into existence, is thus implied. One way of resolving this dilemma is to assume that autopoietic and yet nonliving systems are at least conceivable. Stéphane Leduc (1911) insists that there is no sharp demarcation line separating life from the other phenomena of nature – the passage from the inanimate to the animate is gradual and fuzzy.

CIRCULAR ORGANIZATION

Autopoietic organization is characterized by the circularity and interdependence of component-producing processes. Although such organization either is or is not (circular), and the establishment of an autopoietic system cannot be gradual in a strict sense, there could be a variety of intermediate types of systems in which the autopoietic organization is only a short-lived, transient, or alternating phenomenon. An essentially allopoietic system can attain autopoietic organization for a short time, but being unable to sustain it, because of prevailing unfavorable conditions, it reverts to its allopoietic existence. With "improving" conditions, such autopoietic organization might be able to gradually extend its longevity of existence and become observable

and identifiable as an autonomous system. Consequently, transitional systems *are* conceivable in the sense described above.

Consider the minimal model of an autopoietic system as presented in this volume's introductory tutorial, or in many other related expositions (Varela, Maturana, and Uribe 1974). We assume three types of processes: production (P), bonding (B), and disintegration (D). (The reader is advised to consult the summary of the model on page 8.)

Look at each of the processes as acting independently. Production alone would continue to form more complex macromolecules from simpler elements. As the environmental substrate becomes exhausted, production would either cease or, under certain conditions, resume on the higher level of "elements" (macromolecules). Bonding *alone* would ultimately **[LINE MISSING]** it would cease. For example, stable crystalline patterns might set in. Disintegration alone would simply transform all "organized matter" into a uniform and inert environment of substrate (a state of maximum entropy). | 94

The preceding *hypothetical* examples of singular processes rarely appear in nature. Let us consider multiple processes, say, pairs: Production + bonding transforms the substrate into "crystals." Bonding + disintegration transforms the macromolecules into the uniform environment of substrate. Production + disintegration results in a mixture of substrate elements and higher macromolecules, possibly oscillating around some "equilibrium" proportion. In neither of these cases would we observe an autopoietic system, only allopoietic structures, inert environment, or chaotic mixture.

All three processes are necessary for autopoiesis. But they are not yet sufficient. The processes, P, B, and D, must be conceived of as being *interrelated* if a system is to be identified – they must be organized. We have analyzed P, B, and D in isolation. Suppose that we identify an interdependence between two such processes (P, B). We then test the third process (D), whose properties in isolation we already know, in its dependency on the state of the two others. Can we gain a higher synthetic insight into the behavior of (P, B, D) by such stepwise addition? We c9uld only if the original processes were actually relatively independent .

In autopoietic systems the three processes must be both present *and* interdependent . They must be organized in a circular fashion (their organization must be closed). The products of one process are necessary for another process to take place. That is, disintegration "produces" the substrate necessary for production; production "produces" a catalyst necessary for the production itself and a higher macromolecule necessary for bonding. Bonding "produces" components that assure that their disintegration will "produce" the substrate in a particular locality rather than in a dispersed fashion.

Thus, in this case, we cannot achieve a stepwise assembly of (P, B, D) by first joining P with B and then adding D, for in the absence of D, neither P nor B could take place. The products of D (substrate) are necessary for P and through P for B as well. The coexistence and cooperation of all three processes, P, B, and D, is indispensable for the existence and operation of *any* of them. They must be studied as a whole . This necessity illustrates the dilemma of reductionism and the inevitability of holism.[2] | | 95

Yet, the circular organization of processes is not sufficient in itself: it does not necessarily determine the topology of an autopoietic system. A cleavage, or a distinction, from the environment is needed. A membrane, boundary, or any other kind of separation (or protection) from the environment is a common characteristic of living systems.

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2   It is thus inadequate to concentrate only on the *production* of proteins. The breakdown of proteins, protein *degradation*, is equally important and indispensable. All proteins are degraded and resynthesized many times within the life of a cell. Protein synthesis and degradation are interdependent processes and their understanding cannot be achieved through their separation.

AUTOPOIESIS AND ALLOPOIESIS

Many autocatalytic processes as well as some physicochemical dissipative structures are characterized by the circularity of their organization. Although their organization does not determine their topology, the organization itself is continually being renewed and maintained. As long as the ambient of their autopoiesis is favorable and supportive, there is *no need* for their topological separation and definition. It is only when, gradually, the environment becomes less conducive to autopoiesis that a distinct cleavage and separation of the autopoietic unity becomes necessary for its further maintenance and survival. To define autopoietic systems only through that particular protective structure (membrane) would be overly mechanistic and unnecessary. We raise the following question: Is it possible that, under certain conditions, a circular organization of production processes and an independently emerging local enclosure or membrane could be coupled into a symbiotic and mutually enhancing coexistence, ultimately achieving a unity of organization and structure?

What do we mean by this notion of "symbiosis" of organization and structure? An autopoietic organization can be conceived of either as operating on an essentially unordered environment of components or as acting upon an already ordered, structured milieu, favorable to its enhancement and maintenance. This kind of reasoning is pointing toward the inseparable unity of allopoietic and autopoietic systems.[3]

Allopoiesis is defined as a production of "something else" than itself (Maturana and Varela 1973). This is intuitively clear with respect to man-made machines and artifacts. But what about "natural" allopoietic systems, such as crystals? Are they not capable of producing themselves, even though through a linear, unidirectional organization? The point seems to be in the organization (closed· versus open) and not in the production of "self"' or "something else." Can any system produce itself before being able to produce something else? Can we draw a strict line | of independence between allopoiesis and autopoiesis? Allopoietic systems are undoubtedly the precursors of autopoiesis – allopoiesis is the framework, a condition, within which autopoiesis can take place.

Autopoiesis is inseparable from allopoiesis as much as organization is inseparable from structure. The two emerge and evolve in mutual symbiosis.

CONDITIONS OF BIOPOIESIS

It now appears almost certain that life first emerged nearly 4 billion years ago. The conditions favorable to life on the Earth, characterized by a solid crust, cooler temperatures, and liquid water, could not have been realized, according to our present knowledge, earlier than 4.4 billion years ago. It seems that simple eukaryotic organisms, *Isuasphaera*, might have been extant at least 3.8 billion years ago (Pflug and Jaeschke-Boyer 1979). This would indicate that the emergence of life must have been closely connected with the cooling-off conditions and the accompanying phenomena occuring on the newly formed Earth. In a stricter sense, the emergence of life must have been concurrent with, and actually brought about by, the conditions accompanying formation of the Earth's crust. This short time span of roughly half a billion years was all that was available for the emergence (or an outburst) of life.

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3   The usefulness of the organization-structure duality appears in thinking about such problems as morphogenesis and polymorphism. Both arms and legs are composed of the same types of differentiated cells. The key to their structural differences is not in the cells as such but in the organization of cells within a higher-level unity. Similarly, certain kinds of aphids, although organizationally and genetically identical. exhibit a structural polymorphism of wingless and winged forms.

It was demonstrated that the molecules necessary for life could have been generated by abiotic processes (Miller and Orgel 1974). We should also include meteorites as other possible sources of highly concentrated and localized organic macromolecules. Earth's primordial atmosphere was probably strongly reducing, hydrogen-rich, devoid of oxygen, and saturated by volatiles of carbonaceous chondrites. A liquid, shallow hydrosphere condensed over relatively uniform and yet uneroded crust formations.

The conditions of prebiotic Earth and its short time span indicate that life emerged very swiftly and that the early protobionts lived interspersed within their still favorable surroundings. Any self-replicating genetic system of reasonable complexity could not have assembled itself within such a short "snap" of time; its current uniqueness and complexity must be a result of a long evolutionary process. Similarly, topological boundaries and membranes, appearing as early as 3.8 billion years ago, would not be producible through such primitive "programs" – they would have to be self-organized with the help of other, obviously abiotic, processes. Such topological *biomatrices* then became the most favorable environment for protection, maintenance, and evolution of so far ephemeral, circular, or even autopoietic organizations of component-producing processes. The currently pervasive "organic plasticity" of the topological matrices was acquired gradually through symbiosis and evolution of their **[LINE MISSING]** |

It is therefore submitted that the attempts to explain the origin of life (and autopoiesis) on the basis of exclusively organic components are going to be increasingly frustrated by largely inadmissible retrograde extrapolation of modern life forms and conditions to some 4 billion years ago. It is in the inorganic chemistry of prebiotic Earth (and other planets) where the origins of living organizations must be sought.[4]

Under the assumptions sketched above, life arose *polyphyletically*; that is, many parallel, different, and relatively independent protopopulations occurred at different times and at different locations on Earth. Each such protopopulation gave rise to its own phylogeny, which shared the same basic principles of biochemical organization, reflecting the essential unity of Earth's environment; yet they exhibited often remarkable differences according to their individual localities of origin. Ultimately, they interlocked their evolutionary paths and assumed the dominant isotropy and symbiosis as observed today.

In this sense, all contemporary living systems have already evolved their respective organizations and optimal couplings with their environment. They are fully endowed, completely formed, and relatively perfect end products of these diverse evolutionary pathways. (This is not to deny their continuing evolution, even if proceeding at a much slower rate and in an increasingly ordered and more predictable environment). Bacteria, protists, and unicellular and multicellular organisms are not linearly interdependent "milestones" of a unitary evolutionary process, but are parallel products of intricate symbiotic interactions.

The often noticed morphological homologs between the successive forms characterizing the development of an embryo and the deceptive "succession" of forms acquired by individuals in the "evolution" of species-the "ontogeny recapitulates phylogeny" notion-thus attains a new and potentially powerful paradigmatic quality by contemplating the implications of its reverse: "Phylogeny recapitulates ontogeny."

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4   The 1976 Viking mission to Mars also did not identify any organic molecules in the Martian soil. Yet. some metaboliclike chemical processes were undoubtedly detected. The possibility of ice-eating crystophages or rock-dwelling "bacteria" (see also note 5) cannot be excluded. Searching for organic debris stems from our defining life as a substance, not as a particular (autopoietic) type of organization of substance-producing processes. The failure to interpret the Viking landings phenomena satisfactorily is a sad monument to our naive conception of life: witness "Organic molecules not only make life, they define it and **[LINE MISSING]**.

INORGANIC IMBEDDING OF LIFE

We can characterize life as a phase in the incessant flux of matter, from the mineral to the living and back again from the living to the mineral world. Organisms are closely connected and imbedded in the mineral world. For example, the salt-loving bacteria, halobacteria, can live in dry crystals of salt. They actually disintegrate at low salt concentrations, and | it takes a temperature of 800°C to burn them off.[5] Generally hostile conditions of the purely inorganic world could thus conceivably provide a generating environment for a large variety of protoorganisms during the early stages of Earth's crust formation.

The purely *inorganic* osmotic growths of Leduc display life *analogies* of form, organization, and function (Leduc 1911). An osmotic growth suggests the idea of a living thing at first sight. Osmotic growths are organized of cells or vesicles separated by osmotic membranes. An osmotic stem, formed by a row of cellular cavities, resembles the knotted stems of bamboo.

The analogies of function are also notable. Nutrition consists of the absorption of alimentary substances from the surrounding medium, the chemical transformation of such substances, their fixation by intussusception in every part of the organism, and the ejection of the products of "combustion" into the surrounding medium. Osmotic growths similarly absorb materials from the medium in which they grow, submit them to chemical metamorphosis, and eject the waste products of the reaction into the surrounding medium. They "select" among the substances offered for consumption, absorbing some greedily and entirely rejecting others.

Phenomena of growth and development follow the absorption and fixation of nutrients by osmotic production. It grows, its form develops and becomes more complicated, and its weight increases by hydration. Osmotic growths undergo ontogenic development. In their early youth the phenomena of exchange, growth, and organization are very intense. As they grow older, their exchanges gradually slow down and their growth is arrested. With age the exchanges still continue, but at a much slower rate; even that gradually fails and an osmotic growth dies: it decays, losing both its structure and its organization.

The phenomena of osmotic growth demonstrate how ordinary mineral matter – carbonates, phosphates, silicates, nitrates, and chlorides – may induce the forms of living matter without the intervention of living organisms. Ordinary physical forces are quite sufficient to produce forms like those of living systems, closed compartments containing liquids separated by osmotic membranes, with tissues similar to those of the vital organs in form, color, function, and development.

The chemical composition of the first protobionts and their membranes did not have to be identical with those of modern biological membranes.[6] | More than 3 billion years of evolution of complex protein–lipid interaction suggest that it was mostly inorganic substances that participated in forming the first membranes. These protocells served as templates or functional matrixes for subsequent and gradual "proteinization" of their structures.

Leduc's report on the status of *synthetic biology* contains a wealth of experiments with inorganic osmotic growths (Leduc 1911), These growths exhibit the phenomena of circulation and respiration; they reproduce by budding; they traverse the cycle of growth, plateau, death, and decay. Through their semipermeable osmotic membranes the processes of nutrition are carried

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5   In addition to halobacteria, living organisms are also found at the other extreme: "ice worms," *Mesenchytraeus solifugus*, living in solid blocks of ice of the Artie, exhibit autolysis (i.e., disintegration by its own enzymes at higher than 0°C temperatures).

6   The self-organizing processes in chemistry, apart from synthetic biology, have a long tradition in the literature. Periodic precipitative rings of Liesegang (1898) [see Hedges and Meyers (1926)] or spatial and temporal patterns of A. J. Lotka (1924) are well known. Recently, the oscillating Belousov-Zhabotinsky reaction was invoked by Nicolis and Prigogine (1977) as one of the examples of their dissipative structures.

on. An injury to such an osmotic system is repaired by coagulation of its internal plasma. They are capable of performing periodic movements; they even float freely in their medium or grow out of the solution into the air.

Leduc offers a simple and basic exercise in osmosis: a fragment of CaCh (calcium chloride) is covered by a liquid solution of potassium carbonate, sodium sulphate, and tribasic potassium phosphate. The calcium chloride surrounds itself with an osmotic membrane. An osmotic production, half aquatic and half aerial, emerges. It absorbs water and salts by its base and loses water and volatile products by evaporation from its crown, while at the same time it absorbs and dissolves the gases of the atmosphere.

It is stimulating to contemplate the contrast between the hard crystalline forms of ordinary chalk and these soft, transparent, elastic membranes that have the same chemical composition.

We can induce osmotic growths to produce terminal organs resembling flowers and capsules. When the growth is considerably advanced we can diminish the solution concentration a hundredfold by adding a large quantity of water. Spherical terminal organs will then grow out from the ends of the stems, acquiring conical or other shapes during their further growth.

Corallike forms may be grown from a semisaturated solution of silicate, carbonate, and dibasic phosphate by adding a concentrated solution of sodium phosphate or potassium nitrate. "Corals" are formed by a central nucleus from which large leaves radiate like flower petals. The presence of a nitrate produces pointed leaves with thornlike structures resembling the aloe or the agave.

Funguslike forms may also be obtained, as well as mushrooms, shells, amoeboids, medusas, and many other forms and shapes. Many of these can be allowed to thicken and be taken out of the liquid without breaking. Some growths first rest immobile at the bottom of the vessel. As they grow, they absorb water, their specific gravity diminishes, and they rise up and acquire a considerable degree of mobility.

It should be emphasized that in an osmotic growth the active growing portion is the gelatinous contents of the interior, the external visible growth being only a skeleton or a shell. One can break the calcareous | sheath and draw out a translucid gelatinous cylinder, separated from the liquid by a fine colloidal membrane. | 100

Several hundred other scientists have engaged in synthetic biology, and the literature they left behind is voluminous. For example, Martin Kuckuck of St. Petersburg, Russia, published his *Archigonia, Generatio Spontanea* in 1907. He used a mixture of gelatine, glycerol, and common salt as a substrate, and a crystal of radium as a catalyst. A peculiar culture appeared on the gelatine after 24 hours: a population of cells that grow, divide, and manifest other *external* signs of life.

Soviet academic A. I. Oparin, the proponent of the theory that highly unstable coacervate bags of molecules have mysteriously acquired a living organization, dismissed Kuckuck's experiments as follows: "This was obviously the work of a dilettante who was not sufficiently familiar with colloidal systems, and is, of course, devoid of any real significance" (Oparin 1953).

The point is that synthetic biologists *did* obtain the results they described. They never asserted that their growths were living but were struck by the close resemblance of the growths to the forms of nature. They left hundreds of photographs and detailed descriptions of their experiments. Whether they sufficiently understood the colloids or not, their productions were closer *analogs* of life than anything produced in Soviet biological laboratories so far.

HYPERCYCLES

We have argued that complex organic molecules were conceivably produced by abiotic processes and that inorganic matter is capable of selforganization through basic physical forces, such as for example by osmosis. Compartments, membranes, and other enclosures could emerge from the inorganic milieu of prebiotic Earth. We now have to postulate a self-enhancing symbiosis of such compartments and membranes with the circular organization of component-producing processes.

Eigen and Schuster have proposed the *hypercycle* of nucleic-acid cycles as the minimal system that could bridge the gap between nonlife and life (Eigen and Schuster 1977).

Among the early organic macromolecules were nucleic acids (RNA, for example) and proteins (e.g., polymerases). Proteins can reproduce themselves only by a very roundabout process, and their evolutionary appearance and existence in the absence of RNA is difficult to imagine. On the other hand, RNA molecules replicate simply but rather imprecisely in the abscence of proteins. How do we explain the appearance of proteins from the replication of RNA molecules? A minimal account of specific proteins is needed to assure the accuracy of RNA replication – but the | proteins themselves are coded for by that RNA! As Smith summed up: one cannot have accurate replication without a length of RNA of 200 or more base pairs, and one cannot have that much RNA without accurate replication (Smith 1979). | 101

What is needed to resolve the dilemma described above is a highly potent event: one of the nucleic-acid cycles must join with the existing proteins to produce a protein that would assist a second nucleic-acid cycle to replicate more precisely and faster. That cycle would have to produce a protein assisting a third nucleic-acid cycle, and so on, until the nth protein involves itself in the replication of the *first* nucleic-acid cycle, forming a hypercycle.

It is easier to propose the "hypercycle" as a necessary intermediate stage between nonliving and living than to explain its emergence. Some sort of "natural selection" process must be involved. The circular organization of production and replication processes must be stable, precise, and *protected* from the turbulent environment. A sort of free-flowing molecular soup or broth is certainly excluded.

Amino acids seemed to have been quite abundant in the primitive oceans. In a free ocean the natural selection would favor the growth and more precise replication of each constituent nucleic-acid cycle, but not necessarily the hypercycle as a whole. Given the short time span available for the emergence of the first protobionts, the hypercycles must have evolved relatively fast and in parallel fashion. Compartmentalization of nucleic-acid cycles and membranous enclosures of individual hypercycles would provide the necessary favorable conditions for their further evolution.[7] Enclosed and protected hypercycles could then grow and divide, possibly by budding or fission, and thus establish the first phyiogenetic lineages of individuals.[8]

Such compartmentalization could take place within the cavities of the rocky crusts of vast primordial tidal zones. The inorganic osmotic growths of Leduc's type could also prepare the

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7   Evolution by natural selection thus must take place on the molecular level of hypercycles. The DNA → RNA → Proteins → DNA dynamic systems are selected as wholes even before expressing themselves fully in a particular organism.

8   There is now evidence that 3.5 billion-year-old primitive spheroids, although not necessarily biogenic, exhibit phenomena of cell division (Knoll and Barghoorn 1977).

necessary enclosures for the macromolecular concentrates.[9] Their symbiotic self-enhancement would lead to the *autogenesis* of life. |

AUTOGENESIS

After reviewing some necessary building blocks for our main proposition, we shall attempt to summarize the basic time progression of autogenesis of autopoietic and living systems. The emphasis is on the conditions rather than the mechanisms of such occurrences.

Prebiotic Earth

The formation of Earth's crust and the crystallization of prebiotic rocks stabilized some 4 billion years ago. The interaction of the cooler primitive atmosphere with high-temperature magmatic materials of the crust induced the simultaneous evolution of the primitive hydrosphere as well as masses of igneous rocks. Gradually, standing bodies of liquid water and shallow tidal zones formed. Subsequent water erosion, weathering, and mechanical friction led to the accumulation of sediments and deposits, forming sedimentary rocks, clays, and silts.

The most ancient sedimentary rocks, around 3.8 billion years old, contain traces of cellular structures. For example *lsuasphaera* were detected within the quartz grains or in the silica cement (Pflug and Jaeschke-Boyer 1979). It is assumed that *Isuasphaera* may represent a halfway line between a microspherelike protobiont and the subsequent evolution toward eucaryotes.

The primitive atmosphere consisted largely of water vapor, ammonia, methane, molecular hydrogen and nitrogen, traces of carbon dioxide, and virtually no free oxygen. Earth's crust consisted of rocks made up of a number of different kinds of minerals organized in specific crystalline arrays. These were mostly silicates, sulphates, phosphates, carbonates, and oxides (i.e., inorganic compounds of oxygen, silicon, aluminum, iron, magnesium, calcium, sodium, and potassium).

Note that the macronutrients for most cells are calcium, phosphorus, chlorine, sulfur, potassium, sodium, magnesium, iodine, and iron. Micronutrients or trace elements are manganese, copper, zinc. fluorine, cobalt, vanadium, and selenium – most of these are indispensable for catalytic functions in many enzyme systems. In short, all the necessary components used in experimenting with osmotic growths of synthetic biology were present.

Gaseous bubbles caused countless inner compartments and cavities to solidify within the individual rock chunks. This initial compartmentalization was probably of a higher degree than that of younger metamorphic or sedimentary rocks.

High-energy sources of ultraviolet radiation, electrical discharges, and volcanic and solar thermal energy were abundant. Massive rains and accelerated condensation of waters led to substantial increases in the sho-|reline surface. The regular ebb and flow of the tides, alternately covering and exposing the littoral zone, became pronounced and relatively stable.

Ocean waters cooled to the mild temperatures conducive to biological phenomena but the igneous rocks of the littoral zone were rhythmically exposed to intense solar heat and radiation

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9   Compartmentalization, the formation of vesicles, could also occur through self-organizing forces of the hydrophobic effect. See Tanford (1978), based on the early work of J. W. Gibbs on chemical potentials. Compare also with Leduc (1911) and note 6. Tanford emphasized that hydrophobic forces lead to plastic, deformable structures, uniquely suited for the first critical steps in the organization of living matter. Multiwalled vesicles form spontaneously whenever phospholipids are dispersed in an aqueous medium. Some hydrophobic spherules are formed with the help of electrical discharges.

easily penetrating the ozone-free atmosphere. Daytime and nighttime variations of temperatures on the shoreline were substantial.

Biomonomers

Simple reagents in the atmosphere, high-energy sources, and condensation of water into clouds and rains – these were favorable conditions for simple chemical reactions leading to the reactive compounds of nitrites and aldehydes. Volcanic activity brought simple carbides to the surface and their reaction with superheated water led to the formation of hydrocarbons. Reactive compounds and hydrocarbons are prone to react by themselves and with other reagents at a much faster rate than simpler compounds.

A number of pansyntheses and syntheses occurred and the major classes of biomonomers were produced, namely, alcohols, amines, amides, organic acids, sugars, nucleic acids, porphyrines, fatty acids, carbohydrates, purines, pyramidines, and the like. These monomers were washed down into oceans and water basins, forming dilute aqueous solutions.

The degradation of these compounds was prevented by their dissolution in water; most of the aromatic acids were relatively stable anyway. The concentration of biomonomers was quite low although their variety was significant. Many laboratories have succeeded in random synthesis of nearly all the biologically important monomeric substances, for example, a-amino acids (Miller and Orgel 1974 or Miller 1953).

The more concentrated the reactants are in a solution, the greater is their chance of colliding. Higher pressure effectively concentrates solutions, increases collision frequency, and speeds up reactions. An increase in temperature speeds up the movement of molecules. Adsorption of reactants onto a surface where they are brought closer together leads to a surface catalysis.

Polymers

The next stage is the polycondensation and polymerization of the accumulated simple monomers. New, less energetic reactions, involving dehydrations and phosphorylations, are needed to obtain polypeptides, nucleosides, nucleotides, polysaccharides, lipids, and polynucleotides. A | very dilute aqueous solution of the primeval ocean is a quite improbable environment for dehydration.[10] | 104

One of the principal ways in which more complex materials of life are compounded is dehydration synthesis through condensation, involving subsequent elimination of water. This could happen through evaporation in tidal pools, rock cavities, and temporary basins. The process can be carried out at temperatures above the boiling point of water.

We need a mechanism for concentrating solutes and some catalytic process that would drive dehydration reactions at appreciable rates. The low temperature and low concentration of solutes in primitive oceans virtually precludes any significant polymerization taking place in the seas.

The alternating tidal wetting and drying of littoral zones of the oceanic shores is a massive process that allows temperatures close to 100°C at low tide. Igneous rocks and their compartments absorb and adsorb water, and high evaporation rate leads to dehydration and concentration of solutes, as well as to increased catalytic properties of minerals present . Crystals of

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10 An alternative mechanism is described in Matthews et al. (1977). Helical macromolecules of heteropolypeptides could have synthesized spontaneously in the stratosphere, from hydrogen cyanide and water, without intervening a-amino acids. Their descent on Earth would then contribute to the formation of proteinaceous matrix.

igneous rocks adsorb biological monomers concentrated in their inner cavities and catalyze dehydrations and phosphorylations. During the day the temperatures of concentrations inside metallic rocks could reach 70–140°C and attain highly pressurized conditions. Excess water is evaporated or even boiled away (low atmospheric pressure of the prebiotic Earth), and resulting polymers are screened from ultraviolet radiation and protected from being washed away by tides and rains.

Traces of microcrystalline clays, salts, and other sediments were also concentrating in the nooks and crannies of the rocks and rock surfaces. These clays enhanced the concentration and provided further catalytic capabilities.

It has also been established that the silicates, apatites, phosphates, and other inorganic minerals are not only capable of adsorbing polyphosphates, nucleosides, purines, and pyramidines from the concentrates of internal cavities, but are also acting as catalyzers if the concentration and temperatures are high enough. During low tides a massive evaporation of water left huge quantities of amino acids and some salts concentrated in the internal cavities in a relatively anhydrous condition. Adsorption of some of these acids by crystals of the inner walls of these compartments further facilitated their selective concentration.

For example, glycine and glutamic and aspartic acids are highly absorptive; less adsorptive acids stayed mostly in the solute. High temperatures, high concentration, catalytic action, high pressure-these were the | proper conditions for advanced polymerization of polypeptides, poly- | 105 saccharides, polynucleotides, and other biologically important polymers.

The amino-acid polymerization is a nonrandom process, as are the initial syntheses of bio-monomers. In the same fashion in which the difference in the nature of reactivity of the units of a growing crystal determines the final constitution, so differences in reactivities of the various amino acids serve to promote a definite ordering in a growing peptide chain.

This nonrandomness is now further emphasized by the fact that polymerizations occurred in connection with different minerals, and consequently different adsorptive selections and rates, from a variety of levels of concentrations in cavities of infinitely many sizes and shapes, under different thermodynamic conditions of metallic and nonmetallic rocks, on different beaches, and at different geographical locations.

Still, the same basic monomers were being washed on all beaches and rocks, and the same basic minerals were present, as were the same rhythm of tidal waves and the same alternating solar heat and radiation. These conditions were responsible for the emergence of an only finite, and actually quite limited, number of basic polymers. The enormous diversity in detail but overwhelming unity in essence were the main characteristics later imprinted on the emerging life.

A functional concentrating catalyst must not only provide a unique environment, distinct from the general medium, but must also restrain the reactants at its surface for a sufficient amount of time in order to permit the reactions of interest to occur.

Thus the protective environment of igneous crystalline compartments is absolutely essential because the evolution of biologically important polymers was influenced by some types of rather weak interactions; for example, hydrophobic and hydrogen bonds, both relatively weak and non-covalent linkages, are fundamental to the maintenance of proteins.

Interlude

So, here we are: myriads of igneous cavities on the primeval beaches, each containing a particular concentration of particular polymers, gradually increasing in density with the incessant tidal wetting and subsequent evaporation, engaging in higher levels of chemical reactions, forming more and more complex polymers at increasing rates, with the accompanying increase of cata-

lytic activity. But even the most complex polymer is not a living system. Morphological complexity and dynamiC circular organization of the most primitive organisms are absolutely necessary for metabolism, assimilation, reproduction, and excretion.

What mechanisms organized biological monomers and polymers into autonomous, reproducing units? We do have protected inorganic "wombs," full of highly "pregnant" building materials, exposed to basic biological | rhythms of tides, days and nights, influencing rhythmically the chemical processes inside. We know that the catalytic abilities of mineral crystals steadily increase as a result of the intimate interaction of organic and inorganic matter. The conditions approach the point when the emergence of membranous protocells becomes possible. These originally inorganic membranes continually adsorb organic molecules, and become more elastic and capable of survival, at least for short periods, even in the open waters of their immediate neighborhoods. They contain a variety of interdependent processes, amino-acid cycles, and perhaps some primitive hypercycles.

Membranes of comtemporary cells contain proteins and lipids. Simple lipids contain only carbon, hydrogen, and oxygen-lipids bridge the gap from water-soluble to water-insoluble organic substances. Hydrolysis of simple lipids then yields glycerol and fatty acids. In any case, these compounds could have arisen only through intensified catalytic and even enzymatic functions. These were exactly the processes appearing inside our igneous cavities.

The ability to act as catalysts is characteristic of the majority of substances, especially metals and their oxides, hydrogen and hydroxyl ions, halogens, salts, and the like. Many of these were present in the mineral cavities; others were brought in by tidal waves. Rhythmical changes in temperature led to the formation of unstable intermediate compounds, the substrate-catalysts, decomposing into more complex end-products and restoring the catalysts.

But the catalysts themselves were also changing. Adsorption of the organic material profoundly increased their potentials. Very powerful organic and inorganic catalysts exist, but it is the close interaction of both that leads to the formation of enzymes. Enzymes could be even 10 million times more powerful than the pure crystalline or organic catalysts. Nearly every enzyme requires some inorganic component that in combination with protein dramatically increases its catalytic power.

Enzymes originally evolved inside the igneous inorganic "wombs" at a very early stage. The conditions were perfect. Only basic proteins were needed.

Protein macromolecules are mechanochemical aggregates of common amino acids. Again, they evolved nonrandomly and selectively, at an accelerating rate, inside the cavities. The cavities were i ncreasingly protected by lipids-high temperatures would inactivate most enzymes by denaturing their tertiary structures. As membranes form, dialysis and osmosis cause separation of monosaccharides, amino acids, and nucleotides (small molecules) from polysaccharides, proteins, and nucleic acids (large molecules). However, the simple polymerization, as we have described it, although sufficient for the formation of amino acids, might be too haphazard and undirected for efficient protein formation. A selective | mechanism, governing amino acid sequences in proteins, must have been present.

The evolution of proteins is thus dependent on the existence of a membranous protocell, an ever more efficient hypercycle, and individualization and reproduction of protocells.[11] The "wombs" must ultimately break up and release their contents into the ocean. Forces of natural selection and competition complement the earlier forces of symbiosis.

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11 Other types of "protocells" or Jeewanu-coacervates, liposomes, and proteinoid microspheres-have also been described in the literature (Oparin 1962; Calvin 1969).

Protocell

We said that compounding of proteins and nucleic acids could not be separated from a highly selective functioning of a primitive membranous enclosure of first hypercycles. Crystalline structures of inner walls of igneous cavities provided important surface catalytic effect, and with the help of the adsorption, simple and more complex lipids formed and accumulated internally.

The resulting membrane is however still too passive, does not allow dialysis, and cannot facilitate the formation of proteins.

Another kind of catalysis also took place *within* these spherical enclosures. In addition to the surface catalysis, a "nuclear" catalysis was taking place as well. Catalytic fragments, usually phosphates, often dropped in the middle of the substrate, functioning from within rather than from without the protocells.

When a small piece of crystal drops into the substrate solution. given the favorable conditions existing within the cavities, a catalytic process is started. In a spherical neighborhood of the catalyst, intermediate substrate-catalyst compounds are being formed and a spherical membrane around the nucleus is produced. Outside this inner membrane the substrate is still unchanged and freely interacting with the outer osmotic membrane of the cavity.

The membrane-building polymers are not yet fully bonded and the membrane is initially very fluid and fuzzily delineated. The original " protomembrane" is thus defined dynamically; it is highly volatile, alternately exhibiting disintegration and repair stages. The continuing tidal supply of substrate leads to its gradual strengthening and definition. Depending on the conditions, it might still totally disintegrate by night or at high tide, when the catalytic processes are dampened or the concentration lowered by excess water. But it is bound to reassemble again as conditions become more favorable during the day.

All the vital processes of concentration, dehydration, polymerization, | and the like are continuing. The substrate is being enriched by larger and larger molecules that are being retained within the matrix. Even the catalytic crystal adsorbs additional organic compounds and grows larger and more powerful. The volatile membrane starts to acquire some opaqueness and plasticity and adsorb free porphyrines-the conditions for self-production processes are qualitatively changing and external energy receptors acquired.

There is still no reproduction, no evolution, just myriads of individual entities struggling for their independence from the environmental fluctuations. Their protected rocky "wombs" are indispensable. There are still many million years to go before the first membranes stay intact through the full cycles of outside temperatures and the tides.

In the manner thus described, most likely billions of membranes with or without well-formed nuclei have formed *simultaneously*, at different places on Earth. Fully protected from the harshness of the outside environment, they gradually built their complex structures of chemical relationships.[12, 13]

The rhythms of temperatures and the tides, reliable and never failing, provided for the stability of their inner environments. Continuous restoration of identical, or almost identical, condi-

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12 The separate origin of eucaryotes and procaryotes is now postulated against the naive linear procaryotes to eucaryotes evolution hypothesis. See for example Darnell (1978). It is likely that the basic patterns of genome organization between present-day procaryotes and eucaryotes are correspondingly different. Their independent origin does not preclude their ultimate endosymbiosis, as postulated by Margulis (1970).

13 The early reducing atmosphere (see also note 10) was probably conducive to the emergence of methanogens, anaerobic, methane-producing microorganisms, only vaguely related to procaryotes or eucaryotes. This "third class of life" further supports the idea of polyphylogenesis. Again, structural similarities do not necessarily imply organizational and genetic identity of such autopoietic systems.

tions allowed repeated restoration and duplication of identical molecular chains. Igneous rocks of primeval beaches became teeming with life about 3 billion years ago, 1.5 billion years after the emergence of first protobionts.

Breaking of "Wombs"

The continuing cooling of Earth's crust led into the period of volcanic eruptions, other geological disturbances, and formation of the first mountainous accumulations. The biomatrices were breaking up, releasing their contents into their immediate neighborhoods and ultimately into the forming oceans.

Most of the early protocells obviously did not survive their new environments. Low concentrations, unreliable and more equalized temperatures, ultraviolet radiation, more turbulent waters-these conditions | took their toll. Yet, the complex polymers and macromolecules did not disappear. They found their way back into the remaining matrices and washed over the beach rocks, possibly at more distant places They became factors of the new environment for succeeding generations of autogenesis. | 109

Only the most cohesive unities could survive outside, at least for a moment. Especially in the immediate neighborhoods, in small and partially protected pools of substrate, their survival rate was much higher and they continued to grow.

Ultimately, some of these protocells acquired a critical size and weight and divided through a simple cleavage, budding, or mechanical separation. They were able to devour their less fortunate companions, or their remnants, and incorporate them within their structures.

Their membranous enclosures, simple reproduction, and therefore emerging phenomena of heredity allowed the processes of natural selection and evolution to take place. Ontogeny of the individuals gave rise to shorter- or longer-lived phylogenie chains.

Disruptions of individual ontogenies occurred at different places and at different stages of their development. For at least a billion years, the biomatrices were releasing their contents, starting different phylogenie chains. This process continued until the exhaustion of the matrices or until the outside environment became inhabited by species strong enough to destroy or consume any newly emerging entities. The process of autogenesis slowed down and perhaps even came to a halt. The processes of natural selection, evolution, and structural environmental coupling took over.

It is implied that the basic phylogenie chains were established as a result of differentially interrupted individual primeval ontogenies. The framework of initial speciation, establishment of parallel phylogenie lineages, cannot be separated from autogenesis. *Ontogeny precedes phylogeny* both ontogeny and phylogeny are phenomenological outcomes of the continuing autopoiesis. That is what we meant by our earlier stating that phylogeny recapitulates ontogeny.

The preceding considerations lead to the hypothesis of "instantaneous" appearance of species, at different places and times, and they weaken the notion of phyletic gradualism of ancestor-descendant evolution. Pervasive gaps (both morphological and distributional) in the fossil record are currently labeled as "imperfections." But as stated in Cracraft and Eldredge, for example, there is a growing awareness among paleontologists that our ability to resolve time in the fossil record allows only for "instantaneous " species formation (Cracraft and Eldredge 1979).

The emergence of complex forms (excluding protocells) in the fossil record can be characterized as "instantaneous." The problem of interspecific "missing links" is infamous and the theory of convergent evo- | lution appears a bit artificial and forced. There are also frequent instances of younger fossils exhibiting more primitive traits than older fossils. | 110

This theory has nothing to do with denying evolution: intraspecific variations and geographically isolated interspecific transitions are undeniable. The question concerns species formation, not their evolution and adaptation.

One conjectural implication of autogenesis is the possibility of correlating major outbursts of speciation, properly lagged, with the periods of geological upheavals and disturbances of Earth's crust – the times of breaking of "wombs."

LAMARCKIAN EVOLUTION

The recent resurrection and appreciation of Lamarck's thought does not need much additional documentation. Lamarck's *Philosophie Zoologique* (1809), after being cleaned of the mud of misunderstandings and misinterpretations, is revealing its elegantly crafted beauty of truthfulness. His intuitive respect for the environment is now being experimentally vindicated.[14] We shall mention only a few of Lamarck's thoughts, based on abiogenesis, that seem to be directly relevant to autopoiesis and autogenesis.

Lamarck recognized that in nature there are no such things as classes or orders or families, only individuals. This is a profound observation and is not foreign to the proponents of autopoiesis.

He also rebelled against the then supposed immutability of species. His explanation is a beautiful expression of system-environment structural coupling and of the idea of structural adaptations as compensations for environmental perturbations: "… when an individual of a given species changes its locality, it is subjected to a number of influences which little by little alter, not only the consistency and proportions of its parts, but also its form, its faculty, and even its organization; so that in time every part will participate in the mutations which it has undergone."

Such slogans as "function creates the organ" or "acquired characteristics are inheritable" have little to do with Lamarck's theory. He sum-|marized his doctrine in six points (Leduc 1911): | 111

1. All the organized bodies of our globe are veritable productions of nature, which she has successively formed during the lapse of ages.
2. Nature began, and still recommences day by day, with the production of the simplest organic forms. These so-called spontaneous generations are her direct work, the first sketches of organization.
3. The first signs of an animal or a plant growth being begun under favorable conditions, the faculties of commencing life and of organic movement thus established have gradually developed little by little the various parts and organs, which in process of time have become diversified.
4. The faculty of growth is inherent in every part of an organized body; it is the primary effect of life. This faculty of growth has given rise to the various modes of multiplication and regeneration of the individual, and by its means any progress that may have been acquired in the composition and forms of the organism has been preserved.
5. All living things that exist at the present day have been successively formed by this means, aided by a long lapse of time, by favorable conditions, and by changes on the surface of the

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14 For example, it appears that certain species not only lack detectable sex chromosomes (amphibians), but in many species (alligators, turtles. lizards) environmental temperature is a determinant of sex differentiation. See Bull and Vogt (1979). Constant incubation temperatures of 31°C and above produce females, cooler temperatures of 24–27°C produce males, and, in *Chelydra,* even cooler temperatures (20°C) again produce females. *No* peculiar assortment of genes at conception or even during cleavage can account for these sex ratio biases. Chromosomes seem to be capable of degrading and rebuilding their own components in response to environmental perturbations.

globe – in a word, by the power that new situations and new habits have of modifying the organs of a body endowed with life.

6. Since all living things have undergone more or less change in their organization, the species that have been thus insensibly and successively produced can have but a relative constancy, and can be of no very great antiquity.

There is a grandeur in this view of life.

LESSONS OF SYNTHETIC BIOLOGY

We have described several of the experiments of Leduc (1911) and other synthetic biologists,[15] and attempted to incorporate some of their implications for autogenesis. In summary, at least the following can be noted:

1. The morphogenic action of diffusion produces osmotic growths of extreme variety, resembling closely the forms of shells, fungi, corals, and algae. In addition, the analogy of function is comparable to that of form. The organizing action of osmosis on organic material has hardly been attempted.[16]

2. Many osmotic growths appear to be of great complexity, often *structurally* much more complicated than the simpler forms of living organisms. Osmotic morphogenesis shows that the ordinary physical forces have a power of organization infinitely greater than hitherto supposed. Our ability to distinguish between the osmotic and the living forms in the early fossil record must be carefully reexamined.

3. The growth of an osmotic form structurally resembles the ontogenetic development of the ovum (Weiss 1970; Zeleny 1980). It is at least conceivable to entertain the idea that the beginning of life was not the production of a simple primitive form, from which all others have descended, but that a number of such primitive forms may have been produced, forms that by a rapid physical development attained a high degree of complexity.

4. The physical and chemical conditions of prebiotic Earth were significantly different from anything we can deduce from our immediate experience. The "mineral" world was pervasive – the oxygen, hydrogen. nitrogen, carbon, phosphorus, silica, and lime that now form the substance of living organisms. All living beings are formed of the same elements as those of the mineral world. The term "organic," it should be emphasized, refers to the specific "organization" of these elements, not to a specific organic substance.

5. Every living organism consists of liquids, solutions of crystalloids, and colloids separated by osmotic membranes. A study of the origins of life must include the study of solutions and the study of the physical forces and conditions that can produce cavities surrounded by osmotic

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15 Self-organization experiments with *organic* substances are represented by the work of Guiloff appearing in this volume. Earlier results with *Jeewanu* should also be noted. These "particles of life" consist of peptides. ascorbic acid, ammonium molybdate. a variety of inorganic ions. and a suitable buffer. They exhibit phenomena of growth, reproduction, and metabolic activity. They grow from "within." not from the "outside" like crystals or osmotic growths, their components are not those directly present in the medium but synthesized within the Jeewanu.

16 The nature of species, especially in plants, is a matter of conjecture. D. A. Levin goes even further and submits that "species" are not natural units of evolution – they are *mental constructs* of a community of observers (Levin 1979). This understanding is in direct opposition to Mayr's "Species are the real units of evolution." Such uncritical re-creations of Darwin's *On the Origin of Species* include those of Mayr (1942), Dobzhansky (1941), Huxley (1940), and many others.

     membranes, that can associate and group such cavities, and that can differentiate and specialize their functions.

6. The primeval beaches of prebiotic Earth presented the particular conditions favorable for the production of osmotic growths. An exuberant growth of osmotic vegetation must have been produced in these primeval seas. The soluble salts of calcium, carbonates, phosphates, silicates, and proteinoids became organized as osmotic productions. Billions of these ephemeral forms are long dissolved and without a trace. Many of them left an impression that we often mis-|take for that of a modern living organism. Enough of them became the matrices of life. | 113

CONCLUDING REMARKS

It would be inappropriate to follow the autogenesis further – to the stages of reproduction and evolution. Reproduction, or more precisely self-reproduction, and consequently evolution, appeared only at the later stages of autopoiesis. They are secondary, derived phenomena. Originally, only a multitude of relatively independent ontogenies, nonreproducing autopoietic systems, populated Earth. A successful mechanical fragmentation of an autopoietic unity is a form of self-reproduction – its emergence and subsequent selection were probably quite simple. The reader is advised to consult the recent works of Maturana (Maturana 1980) and Varela (Maturana and Varela 1973) on these topics.

    The concept of evolution, as it becomes modified from the vantage point of autopoiesis, is a fascinating but too lengthy topic to handle within a single paper. There are basically two ways of treating evolution within autopoiesis, both radically different from the currently prevailing notions.

    In both, evolution is a secondary (i.e., derived) phenomenon of autopoiesis. This is in contrast to the pivotal position accorded to it, for example, by Dobzhansky et al. (1977): "Nothing in biology makes sense except in the light of evolution."

1. Evolution takes place only when there are organizational changes occurring throughout the sequentially interdependent self-reproductions of unities. Only sequentially reproducing patterns of *organization* can evolve – if changes are occurring during the reproduction of that pattern. An invariant organization, manifesting itself through a pattern of *structural* transformations of a unity, is undergoing *ontogenesis,* not evolution. In this view, nonreproducing entities (e.g., embryo, Earth, universe) do *not* evolve but are undergoing ontogeny. Also, organizationally invariant unities (e.g., species) do not evolve but only have a history of structural adaptations (i.e., undergo ontogeny) (Maturana and Varela 1973).
2. Evolution takes place whenever there is a hereditary *structural* change in the sequentially self-reproducing, but organizationally invariant, unities. In this view, establishment of a phylogeny is necessary and sufficient for evolution. In this framework, the nonreproducing entities do not evolve, but the organizationally invariant classes, as for example species, do. Evolution consists of the history of structural changes that the members of a phylogeny undergo.

    Both of these views are consistent with autopoiesis. The first refers to | the structural changes | 114
within a given identity class (invariant organization) as ontogeny and would label as evolutionary only the changes pertaining to the organization. The second view allows for evolution within a given identity class, thus labeling as evolutionary the changes of structure.

    The second view is less radical and closer to our common usage and understanding of evolution. The first view is potentially more significant, but possibly should not be referred to as "evolution." Perhaps *structural* and *organizational* evolution, in all of their interdependence, might fruitfully reflect this duality.

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