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THE GENESIS MODEL
PART I: COMPLEXITY, A MEASURE FOR THE EVOLUTION OF SELF-ORGANISED SYSTEMS OF MATTER

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Abstract

Cosmic, molecular, biological and human evolution are analysed in terms of the systems approach introducing a quantitative measure of complexity C = IR (where I is the average selective information per energy state of elementary element, and R is the energy redundancy of the system). A classification of self-organised systems according to their complexity suggests a general law. The first law of genesis: $\Delta C \geqslant 0$, i.e. the complexity of a self-organised system increases or remains constant. If the first law of genesis holds, the second law of thermodynamics in its microscopic formulation defining entropy in terms of the number of "complexions" of a system is a special case of $\Delta C \geqslant 0$, valid only in the case that the variety of relations measured by the energy redundancy R of a system remains a positive constant.

1. INTRODUCTION: THE PROCESS OF EVOLUTION

Evolution, this is the history of self-organisation of matter into more and more complex systems[1].

From the formation of the universe up to present reality the process of evolution is described in more or less details within the framework of special sciences. Some steps of evolution are not only described as a historical sequence of phenomena, but also fairly well explained within special theories. Such nuclear astrophysics can explain the formation of chemical elements in terms of nuclear reactions and gravitation; neo-Darwinism can explain the evolution of biological species in terms of genetic mutations and natural selection.

Several authors — surpassing the scope of *their* special science (paleontology, microbiology or astrophysics) — have tried to give an explanation for the process of evolution in general. The proposed answers are quite unclear and contradictory, explaining the process of evolution as a realisation of a plan of God converging to a magic point "Omega"[2], or as a magic mixture of a little bit of "chance" and a little bit of "necessity"[3], or stating with the words of an astrophysicist the simple axiom, that in the universe "there is rather music than noise"[4] seem to us not scientific hypothesis but rather poetic circumscriptions of the metaphysical convictions of the respective authors. If we insist on this point, so only to emphasise the *need* for interdisciplinary research concerning the process of evolution in general, that is, comprising physical, chemical, biological and human systems.

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New approaches emerge in the works of Prigogine, studying the self-organisational aspects of thermodynamical systems far from the equilibrium state and re-examining our conception of time.[5] Eigen and his co-workers attempt to arrive at a theory for the self-organisation of systems of macromolecules using concepts of information theory and game theory[6-8].

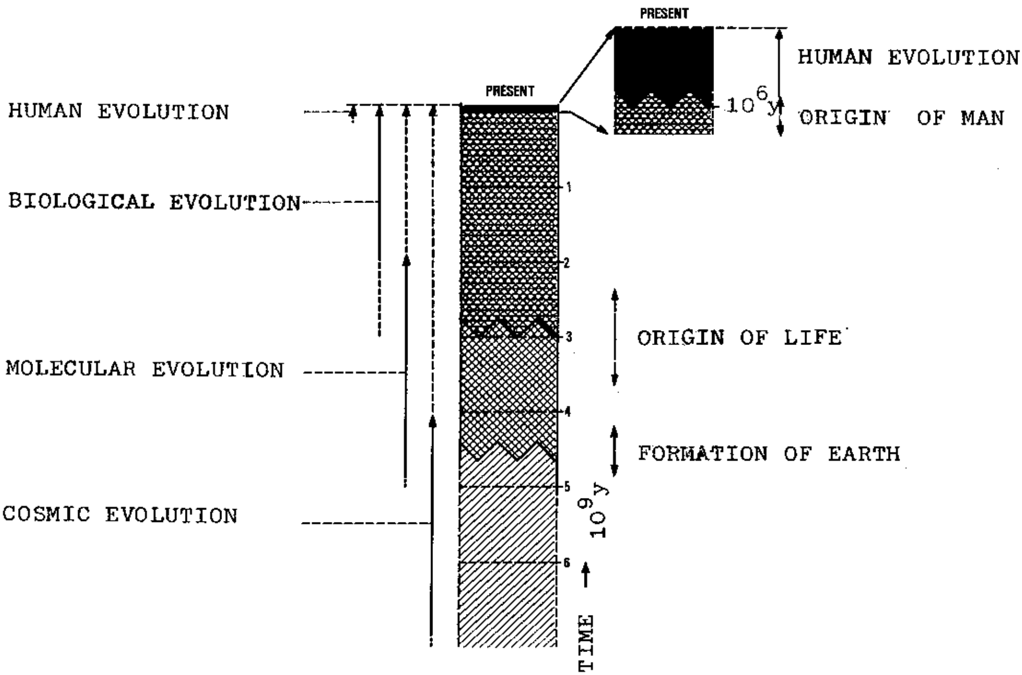

Figure 1. Time and evolution (after de Rosnay[9]).

2. CLASSIFICATION OF THE PHENOMENA OF EVOLUTION

From an heuristic point of view, today's knowledge concerning the process of evolution in general could be compared with the situation of chemistry around 1865 or with the situation of elementary particle physics around 1964.

(i) Arbitrary classification of known phenomena. The variety of chemical elements or the variety of hadrons at the respective times had been classified in a rather arbitrary way using as classification criteria the alphabetical order of the element's or particle's symbol or the historical order of discovery. The heuristic limits of such an approach are quite evident — no way to determine the *completeness* of the known ensemble of elements or particles, and no *predictive* value, that is, no indication about the future evolution of the ensemble.

(ii) Classification revealing order. The genius of Mendeleev and Gell-Mann consisted not only in intuitively supposing a hidden order in an apparently chaotic card-game of phenomena, but also in proposing new criteria of classification, which make this order apparent.

(iii) A general classification criterium for all known phenomena of evolution? The classical approach to put an "order" into the vast ensemble of

the phenomena of the process of evolution known today is to present them in the form of a historical sequence as summarised in Figure 1 (above): formation of the universe (big bang), formation of the solar system and the earth, chemical synthesis in a primitive atmosphere, accumulation of chemical compounds, complexification of molecules, formation of self-reproducing units, appearance of photosynthesis, appearance of respiration mechanisms, organisation of multi-cell aggregates, formation of a primitive central nervous system, evolution of "higher" forms of life, formation of cortex, appearance of warm-blooded animals, organisation of cortex, animal-man transition, self-consciousness, critical reflecting consciousness, abstract logical thinking, systematic scientific research, ...

The major drawbacks of such a historical enumeration — however detailed it may be — are the same as mentioned under (i): no way to determine the completeness of the list and no predictive value.

In analogy to the Mendeleev and the Gell-Mann scenario one could look for a classification criterium revealing some sort of order in this vast ensemble of phenomena. Bresch[10] proposed a classification of self-organised systems — he calls them "patterns" — according to the number of elementary particles contained within a "pattern".

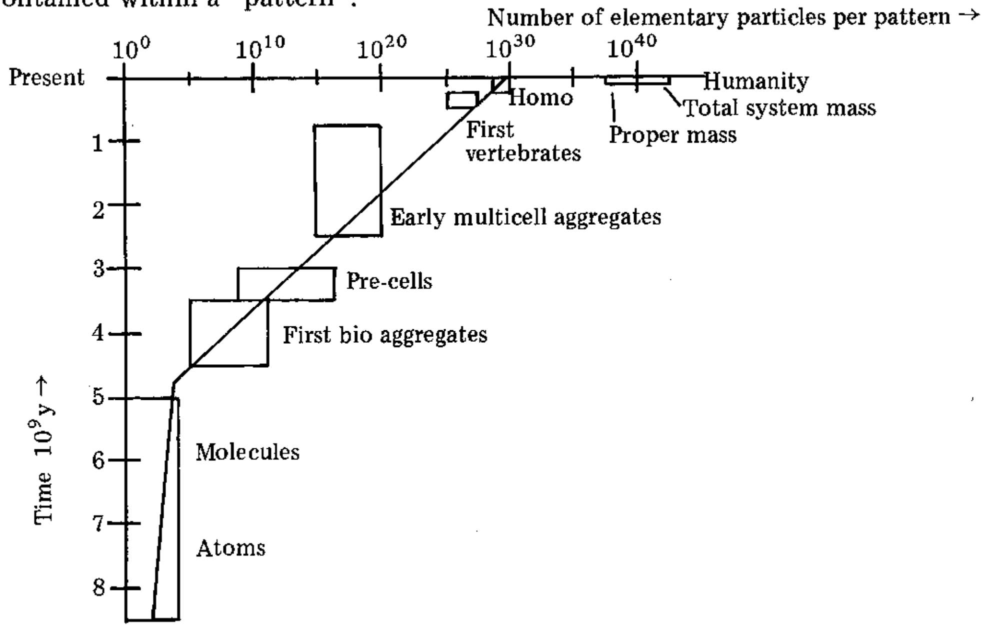

Figure 2. Evolution and the number of elementary particles (nucleons + electrons) per self-organised "pattern" (after Bresch).

In comparison with Fig. 1, the classification of Fig. 2 above already reveals some sort of regularity; an exponential growth of the number of elementary particles per self-organised "pattern" at least in the biological phase of evolution. Bresch himself states the limits of his quantitative approach. The number of elementary particles contained within a pattern is not a *unique* measure for its complexity or degree of evolution. (An iceberg or a star cannot be situated on the above "curve".)

Summarising, we can say that so far there exists no satisfying general and quantitative criterium for the classification of the phenomena of evolution, but on the other hand — as stated in the initial sentence of this article — there seems to be agreement among astrophysicists, biochemists, biologists etc., that the process of evolution follows a recognisable and unchanged direction: from "less complex" to "more complex" systems of matter.

3. A QUANTITATIVE MEASURE OF COMPLEXITY

(i) What is more complex? Intuitively we seem to know what is meant by the term "complexity". Everybody would agree that a human being is more complex than a cell, that a cell is more complex than an atom of hydrogen, but given two systems A and B, how could one determine in a *quantitative* way whether system A is more complex than system B or vice versa? As stated above, the number of elementary particles contained within a system is an indication of its "complexity" but not a sufficient measure, for example, which of the two systems of nucleons is more "complex": (U_{92}^{238}) or ($Th_{90}^{234} + He_2^4$)?

As long as the term "complex" is used by different authors in a rather arbitrary way, any discussion about "increasing complexity" is without meaning.

(ii) A definition of complexity. The systems approach developed at M.I.T. in the years 1940-1970 based on the works of N. Wiener, W. McCulloch, J. Forrester, etc., could be considered as a scientific approach complementary to the classical analytical approach.[1] This heuristic tool has been applied quite successfully to complex phenomena like living systems, eco-systems and economic systems. In analogy to a German proverb ("Er sieht den Wald vor lauter Baumen nicht — he can't see the wood for the trees"), one could characterise the systems approach as being more concerned about the behaviour of the total system (the "wood"), in opposition to the analytical approach being mainly concerned about the behaviour of single elements (the "trees").

In the terminology of the systems approach, the notion of the *complexity* of a system is linked to the following points[1]:

- A complex system is constituted by a great *variety of elements* or components having specialised functions.
- These elements are organised in internal *hierarchical levels* (e.g. cells, organs, systems of organs, organisms, etc.).
- The different levels and the individual elements of a complex system are linked by a great *variety of relations*.
- The interactions between elements of a complex system are of the non-linear type.

(iii) Towards a measure of complexity. A quantitative comparison of the complexity of two different systems would imply at least two measurable variables: (a) a measure for the *variety of elements* and the hierarchical organisation of these elements; and (b) a measure for the *variety of relations* between these elements. In the following we will define such quantitative measures for complex systems organised in one level only, and then extend these definitions to complex systems organised in several hierarchical levels.

(iv) A measure for the variety of elements. Let us consider a complex system composed of N elementary elements organised in one level only. Assuming that the N elementary elements can be divided into M mutually exclusive *types* of elementary elements, the system can be described in the following way:

- identification index of elementary element type: 1, 2, . . . i . . . M
- number of elements of a given type: $n_1, n_2, \dots n_i \dots n_M$ with

$$\sum_{i=1}^{M} n_i = N$$

So the variety of elements of the system would be completely defined by the M-tuple of natural numbers $(n_1 \dots n_M)$. Since the handling of multi-dimensional variables is quite cumbersome, we try to arrive at a single variable as compound measure of $(n_1 \dots n_M)$.

As pointed out by Eigen[7], N. Wiener already proposed that information be regarded as a new variable in physics. In fact, replacing the terms "discrete source of information" or "message repertoire" by the more general term "complex system" and the terms "sign of an alphabet" or "message type" by the more general term "elementary element type", the average selective information rate per sign generated by a discrete source as defined in communication theory[11] can be applied as compound measure for the variety of elements of the above complex system. Introducing the relative frequency per element type: $p_1, p_2 \dots p_i \dots p_M$ with $p_i = n_i/N$ and

$$\sum_{i=1}^{M} p_i = 1$$

we define the average selective information per elementary element type as compound measure for the variety of elements of a complex system organised in one level only:

$$I = -\frac{1}{\ln 2} \sum_{i=1}^{M} p_i \ln p_i \text{ [bits]} \tag{1}$$

Simple examples: The variety of elements of a system composed of one elementary element only, e.g. a single proton, can be described by I = 0 bits; and a system composed of only two different elements belonging to two different types, e.g. a deuteron constituted of a proton and a neutron, by I = 1 bit.

(v) A measure for the variety of relations. Assuming that one could determine the total number of relations between the elements of the considered complex system and assuming that the total number of relations could be divided into a finite number of mutually exclusive types of relations, one could in analogy to (iv) arrive at a complete description of the system by determining the absolute or relative frequencies of each type of relation and define a compound measure for the variety of relations in terms of these frequencies.

In practice, for a large number of elements — given only a few types of relations — this approach would yield astronomical numbers difficult to determine. In search for a measurable compound variable for the variety of relations between the elements of a complex system we have developed the following approach. Assuming that *each* relation between two elements of a system results in a difference of the energies at rest (or rest masses) of the two elements in the related state and the same two elements in the unrelated or free state, we define a compound measure for the variety of relations of a system in terms of the energy difference between the sum of the energies at rest of each elementary element in the unrelated or free state and the energy at rest of the total system, that is, the ensemble of related elementary elements. Thus the system can be described in the following way:

- identification index of elementary element type: 1, 2 . . . i . . . M where M is the number of element types
- energy at rest or rest mass of one elementary element of the given type in the unrelated or free state: $e_{1o}, e_{2o} \ldots e_{io} \ldots e_{Mo}$
- number of elements of a given type: $n_1, n_2 \ldots n_i \ldots n_M$ with $\sum_{i=1}^{M} n_i = N$ the total number of elements
- energy at rest or rest mass of the total system: E_o.

We define the energy redundancy R as compound measure for the variety of relations between the elements of a complex system:

$$R = \frac{\sum_{i=1}^{M} n_i e_{io} - E_o}{\sum_{i=1}^{M} n_i e_{io}} \times 100\,[\%] \tag{2}$$

Simple examples: The variety of relations of a system composed of one elementary element only, for example a single proton, can be described by R = 0%, and a system composed of two different elements belonging to two different types, for example a deuteron = (proton, neutron) by

$$R = \frac{(m_p + m_n) - m_d}{(m_p + m_n)} \times 100 = 0.11846\%$$

(vi) Extension of the definitions of I and R to complex systems organised in several hierarchical levels. Let us consider a complex system composed of N elementary elements organised in L hierarchical levels. Assuming that the N elementary elements can be divided into M mutually exclusive types of elements and that each element of a given type can exist only in one of L discrete energy states — each energy state corresponding to a hierarchical level — the system can be described in the following way:

- identification index of elementary element type: 1, 2 . . . i . . . M
- identification index of the energy state of an elementary element of a given type i: i1, i2 . . . ij . . . iL (i = 1 . . . M)
- number of occupation of energy states of a given elementary element type i: $n_{i1}, n_{i2} \ldots n_{ij} \ldots n_{iL}$ (i = 1 . . . M) where L is the total number of energy states with

$$\sum_{j=1}^{M} n_{ij} = n_i$$

the number of elements of type i, and

$$\sum_{i=1}^{M} \sum_{j=1}^{L} n_{ij} = N$$

the total number of elementary elements.

Introducing the relative frequency of energy states of a given elementary element type i: $p_{i1}, p_{i2} \ldots p_{ij} \ldots p_{iL}$ (i = 1 . . .M) with $p_{ij} = n_{ij}/N$ and

$$\sum_{i=1}^{M} \sum_{j=1}^{L} p_{ij} = 1$$

we define the average selective information per energy state of elementary element as compound measure for the variety of elements of a complex system organised in several hierarchical levels:

$$I = -\frac{1}{\ln 2} \sum_{i=1}^{M} \sum_{j=1}^{L} p_{ij} \ln p_{ij} \text{ [bits]} \tag{3}$$

Concerning the variety of relations definition (2) of the energy redundancy of a system is taken without modification as compound measure for the variety of relations of a complex system organised in several hierarchical levels.

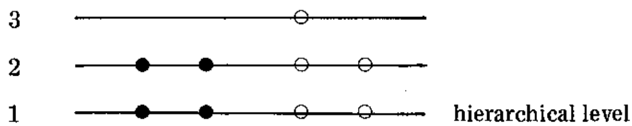

Figure 3. Be_4^9-nucleus, example of a hierarchically organised system of nucleons. (● proton, ○ neutron.).

Simple example: Figure 3 (above) shows schematically a simple example of a hierarchically organised system of nucleons. A Be_4^9-nucleus can be described as a system of $N = 9$ elementary elements, with $M = 2$ types of elementary elements (protons, neutrons), organised — assuming the shell model — in $L = 3$ hierarchical levels. With the relative frequencies of energy states of the two elementary element types $p_{11} = 2/9$, $p_{21} = 2/9$, $p_{12} = 2/9$, $p_{22} = 2/9$, $p_{13} = 0$ and $p_{23} = 1/9$, definition (3) yields as compound measure for the variety of elements of the system $I = 2.281$ bits. Definition (2) yields as compound measure for the variety of relations of the system

$$R = \frac{(4m_p + 5m_n) - m_{Be^9}}{(4m_p + 5m_n)} \times 100 = 0.6823\%$$

(vii) A unique measure of complexity. The variable I as defined in (3) and the variable R as defined in (2) describe in a quantitative way the "complexity" of a system, but still do not answer the question, which of two systems A and B is more complex. In order to arrive at a single variable C for the complexity of a system, we introduce a functional relationship between I, R and C.

$$C = f(I,R) \tag{4}$$

Since a quantitative definition of C should correspond to our intuitive notion of complexity, the value of C should increase with the variety of elements of a system measured by I, and also increase with the variety of relations of a system measured by R.

Thus the following definition

$$C = I\,R \tag{5}$$

seems to us a simple and reasonable quantitative measure for the complexity C of a system. The units in which C is expressed [bits] might appear unconventional, but Shannon's quantitative definition of selective information appears also puzzling at first sight.

Example: Using definitions (2), (3) and (5) we now can answer the question posed in section 3.(i): Which of the two systems of nucleons is more complex: (U_{92}^{238}) or (Th_{90}^{234} + He_2^4)? The values of the complexities C of the respective systems, calculated on the bases of the shell model are 5.5587 and 5.5718 bits, so according to our definitions the system (Th_{90}^{234} + He_2^4) is more complex than the system (U_{92}^{238}).

4. THE FIRST LAW OF GENESIS

In agreement with the qualitative statement in section 2.(iii), that the process of evolution follows a recognizable and unchanged direction from "less complex" to "more complex" systems of matter, we postulate the following general quantitative law:

The first law of genesis: The complexity C of any self-organised system of matter increases or remains constant

$$\Delta C \geqslant 0 \tag{6}$$

To verify the general validity of this hypothesis goes far beyond the scope of this speculative paper. We have limited ourselves to a few quantitative checks concerning systems of nucleons only, but the results are encouraging.

- Hypothesis (6) holds throughout the chain of natural radioactive decay from U^{238} to Pb^{206}. Interesting to note is that in the case of α-decays the value of I of the system remains constant with the value of R increasing, while in certain cases of β-decays the value of R decreases, but is compensated by an increase of the value of I. Therefore the notion of radioactive "decay" seems to us a misnomer, since with each "decay" the complexity of the system increases.
- The different postulated nuclear reactions leading from H^1 to He^4 within stars, as well as the reactions of the CNO-cycle are also in agreement with (6).

5. THE SECOND LAW OF THERMODYNAMICS, A SPECIAL CASE OF THE FIRST LAW OF GENESIS?

Let us consider an "isolated system" of N identical molecules of an "ideal gas".

(i) The approach of the Genesis model. Considering the gas molecules as elementary elements of the system, the number of elementary element types M = 1 by definition. Following the arguments developed in section 3.(vi) we assume that each elementary element can exist in only one of L discrete energy states. Since there exists only one type of elementary elements, we can omit in our notations the first index i=1 identifying the elementary element type and describe the system as follows:

- identification index of the energy state of an elementary element: $1, 2 \ldots j \ldots L$
- number of occupation of energy states: $n_1, n_2 \ldots n_j \ldots n_L$ with

$$\sum_{j=1}^{L} n_j = N$$

Introducing the

- relative frequencies of energy states: $p_1, p_2 \ldots p_j \ldots p_L$ with $p_j = n_j/N$ and
$$\sum_{j=1}^{L} p_j = 1$$
the average selective information per energy state is given according to (3) by
$$I = -\frac{1}{\ln 2} \sum_{j=1}^{L} p_j \ln p_j \text{ [bits]} \qquad (7)$$

The energy redundancy of the system is given according to (2) since M = 1 by
$$R = \frac{Ne_o - E_o}{Ne_o} \times 100\,\% \qquad (8)$$
with N the total number of molecules, e_o the energy at rest or rest mass of one molecule in the unrelated or free state, and E_o the energy at rest or rest mass of the total system.

The complexity C of the system is given according to (5) by C = I R. Since we have specified that the considered system be "isolated" and that the elementary elements of the system are identical molecules of an "ideal gas", N, e_o and E_o are constant by definition throughout the evolution of the system. As a consequence according to (8) R = const. or $\Delta R = 0$. If the first law of genesis (6) holds, we can write in the case that $R > 0$:
$$\Delta C = \text{const. } \Delta I \geqslant 0 \qquad (9)$$
that is, the average selective information per energy state of elementary element increases or remains constant for an isolated system of molecules of an ideal gas.

(ii) Boltzmann's approach of complexions. Assuming that each molecule can exist only in one of L discrete states of motion, the system can be described in the following way:

- identification index of state of motion: $1, 2 \ldots j \ldots L$
- kinetic energy of state of motion: $\epsilon_1, \epsilon_2 \ldots \epsilon_j \ldots \epsilon_L$
- number of occupation of a given state: $n_1, n_2 \ldots n_j \ldots n_L$ with
$$\sum_{j=1}^{L} n_j = N$$

A compound or "macroscopic" description of the system is given, introducing the internal energy U and the entropy S of the system:
$$U = \sum_{j=1}^{L} n_j \epsilon_j \qquad (10)$$
and
$$S = k \ln w \qquad (11)$$
where $w = N!/(n_1!n_2! \ldots n_j! \ldots n_L!)$ is called "number of complexions" (that is, the number of distinct combinations of N elements yielding the number of occupations of the different energy states $n_1, n_2 \ldots n_L$), and k the universal Boltzmann constant. If the second law of thermodynamics holds, we write:
$$\Delta S \geqslant 0 \qquad (12)$$
that is, the entropy of the system increases or remains constant.

(iii) The equivalence of both approaches for large N. Replacing in (11) the factorials ln n! by (n ln n—n) according to the approximation of Stirling

and replacing in (7) p_j by n_j/N one can easily show that for large N:

$$S \cong I\,k\,N\,\ln 2 \tag{13}$$

or since k, N and ln 2 are constants, $S \cong$ const. I. Thus for an isolated system constituted of a large number of molecules of an ideal gas $\Delta S \geqslant 0$ (12) is equivalent to ΔC = const. $\Delta I \geqslant 0$ (9).

In summary: If the first law of genesis (6) $\Delta C \geqslant 0$ holds, then we can deduce that the second law of thermodynamics in its microscopic formulation defining entropy in terms of the number of complexions of a system is a special case of (6), valid only in the case that the variety of relations measured by the energy redundancy R of a system remains a positive constant.

6. CONCLUSION OF PART I

Applying the second law of thermodynamics to the universe as a whole leads to considerable conceptual difficulties concerning the process of evolution, which seems to contradict this principle. Boltzmann himself wrote: ". . . with all recognition of the caution, which is necessary in such deductions concerning the universe as a whole going beyond experience, one has to admit that this consequence [of the second principle of thermodynamics] is not very satisfying and lets the discovery of a generally satisfying way out appear to be desirable."[(10)] Should the first law of genesis reveal to be the desired "way out"?

Certainly the arguments brought forward to support our hypothesis are very limited; besides a more detailed analysis of systems of nucleons, it would be interesting to test our hypothesis for self-organised systems of molecules and to apply the concept of increasing quantitative complexity to DNA-systems and systems of biological species, which would necessarily lead to a revision of the neo-Darwinian concept of mutation and natural selection. Since in the case, that our hypothesis holds, only mutations which increase the complexity of a given DNA-system are maintained, and the population increase or decrease of a given species depends only on the complexity of a total eco-system.

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