ISSN 2976 - 730X
IPI Letters 2025,Vol 3 (4):25-43
https://doi.org/10.59973/ipil.262

Received: 2025-08-25
Accepted: 2025-09-18
Published: 2025-09-25

Article

Information and modular universal evolution

Zyri Bajrami[1,*]

[1]Department of Biology, Faculty of Natural Sciences, University of Tirana, Tirana, Albania

*Corresponding author: zyri.bajrami@fshn.edu.al

Abstract - Matter, energy, and information are inseparable, as energy and information are intrinsic properties of matter. In this framework, energy activates matter, while in-formation enables its organization. Atoms and molecules, as units of interaction in the non-living world, and modules, as biological and socio-cultural units in the living world, are formed through the dyad of self-organization and selection in interaction with matter (M), energy (E), and information (I). Based on these interactions, and in relation to time, the Modular Evolution Model (MEM) has been developed, from which the following equations are derived: E = Mi, M = E/i and i = E/M. The values of i in these formulas, reflect the ratio of time and information before and after an evolutionary event, such as the emergence of a taxon. The history of matter is understood as a process of its modularization and energization over time, during which the values of information (I), self-organization (so), and energy (E) increase, while those of natural selection (ns), matter (M), and mass (m) decrease. Through the interplay of interaction units and modules as intelligent agents, and through selection, stability or autonomy is achieved. In the first stage, selection acts on the structure of interaction units and modules formed through self-organization processes. In the second stage, selection applies to these units and modules as they interact with the environment and with other modules, giving rise to semantic in-formation. Finally, the advantage of Universal Modular Evolution (UME) over the Modern Synthesis (MS) and the Extended Evolutionary Synthesis (EES) is highlighted.

Keywords - Universe; Matter; Energy; Information; Modules; Unit of interaction; Self-organization; Natural selection; Intelligent agent; Autonomy; Universal modular evolution.

1 Introduction

When chemists frequently use the term 'molecular recognition', even publishing a scientific journal dedicated to the field, how is it that many scientists still accept only non-physical, immaterial information, to the extent that the concept of material information suggested by R. Landauer [1] is still under debate? Meanwhile, in biology, some problems are solved using C.A. Shannon's (1948) [2] negative entropy formula, especially when communicating in-formation between the sender and receiver of signals. Rightfully, such opinions, though not frequently, have been mentioned in scientific settings, including that of Nobel Prize Winner J. M. Lehn [3] who stated that information fuels evolution; interactions are a consequence of information [4], evolution is the growth and acquisition of information [5], semantic information exists even in organisms without nervous systems [6], information is both concrete and abstract [7]; there exists structural and functional information [8], information is an attribute of matter [9] etc. We mentioned only a few authors who defined information about both material and non-material systems of the world.

We believe that information is a property of the elements that compose both material and non-material systems, enabling their interaction within and between systems, and forming the structure of modules that act as an intelligent agent [10] [11]. This definition highlights the importance of information for system formation. When a system is defined as a set of elements that interact with one another [12] it implies the presence of information as a property of matter that enables interaction and the organization of matter.

Around three decades ago, T. Stonier [13] [14] wrote that just as energy is the capacity to do work, information is the capacity to enable interaction and the organization of matter. L. Hartwell and his colleagues [15] with the idea that the future requires research not on individual components but on systems, introduced a notion that warned of a shift from molecular biology to modular biology. Meanwhile, it has been increasingly acknowledged that modularity is a general principle in living organisms [16] [17], in language [18], in human societies [19] and so on. On the other hand, S. Kauffman [20] introduced the idea of a "marriage" between natural selection and self-organization, from which a new order may emerge. It was also concluded that self-organization is a process through which global behavior emerges from the interactions of the system's lower-level elements [21] and that the two fundamental molecular processes are self-organization and molecular recognition or information [22].

Recently, physicist M. Vopson [23] formulated the principle of the equivalence of matter, energy, and information. According to this principle, information is considered the fifth form of matter state, alongside the four classical states—solid, liquid, gas, and plasma. In contrast, it is stated that information is non-local, does not emerge in particle form, and therefore has no mass [24]. In conclusion, the theoretical basis of this study is supported by the following four concepts.

- Matter is everything, but matter without energy is not active, and without information, it cannot be organized [25]. This idea demonstrates that the three categories of the universe are inseparable from one another.
- The nature and properties of information are physical laws that, although not intentionally designed, manage to perform such processes [26]. Just as in biology, everything makes sense only in the light of evolution [27] so too does everything in the universe find explanation only in the light of information.
- In Assembly Theory [28] [29] efforts are made to define the complexity index of an object, which was previously mentioned in Algorithmic Theory. According to algorithmic theory, the complexity of an object is the shortest computer program of its formation. It is no coincidence that today the metaphor of the universe as a Giant Computer is often used [30].
- In physics, information is not seen as an object but as a property of the correlations between the elements of the system [24].

This means, as mentioned earlier in the definition of information and as I will attempt to argue below, that this information enables the system to behave as an intelligent agent. What we aim to argue in this study is that universal modular evolution occurs not only through natural selection of interaction units or modules formed during self-organization processes and influenced by other factors such as matter, energy, and information, but also through how these modules acquire stability, autonomy, or static persistence.

From these interactions of the factors of evolution, both among themselves and with time, the model of universal modular evolution has been established, expressed through the formula E = Mi.

2 Modules

2.1 Modules Are Real Demons: Definition of Information

As mentioned in the introduction to this study, the factor that makes what E. Schrodinger [31] calls organized matter possible is information as property of this matter. Accepting the idea that information is a property of matter undermines the concept that information in a system comes from the outside [32,33]. Let's look at Figure 1 where in a container divided into two parts, there are two molecules, one red and the other green. In placing the molecules in a container with two partitions, an observer distinguishes four microstates (Figure 1).

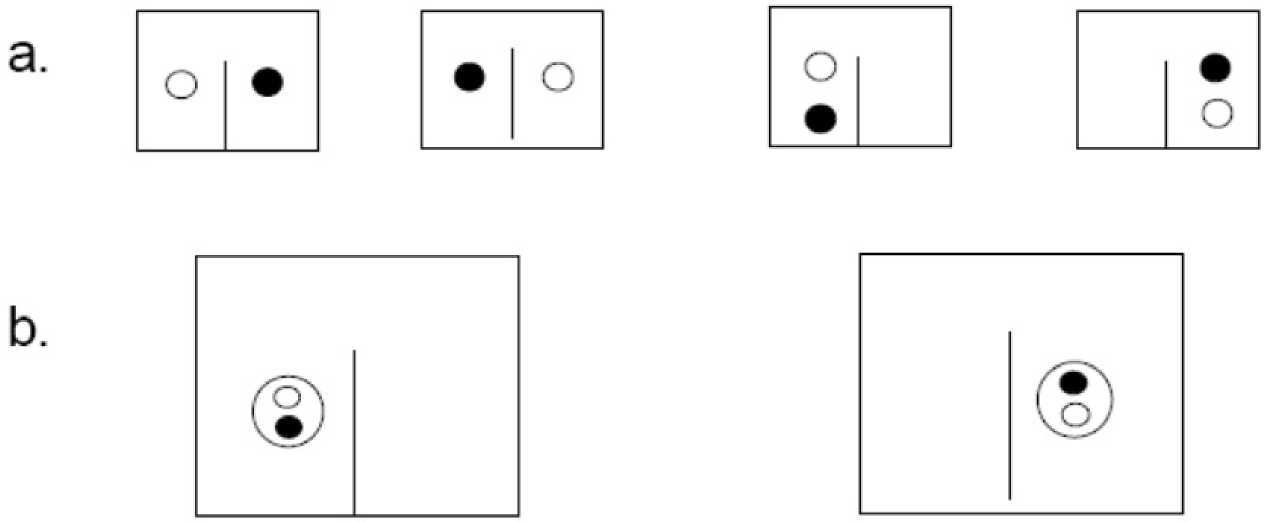

Figure 1: Four micro-states of two molecules (red and green) in a container divided into two parts (a) and two states (b) (According to [32]).

Let's assume that the two molecules are the enzyme and its substrate. As a result, they bind together in the region of their steric or chemical information (Figure 1b), and the observer discerns only two microstates. We also assume that due to a physical barrier, the enzyme-substrate aggregate does not pass into the neighboring compartment of the container. After a while, the observer notices several microstates because a container separation can be formed by one or more aggregates. Above all, it is expected to find a group of molecules formed in a corner of each compartment without the intervention of the imaginary demon. The factor that produces organized matter must be sought within the matter itself and not outside it or the container. The two halves of a container are different be-cause the information is a change that makes a difference [34], or because something becomes a source of information when it is present in two or more states [35]. From here, we formulate the definition of interaction information: The information of interaction is the property of the constituent elements of material and non-material systems that enables their interaction both within and between systems. This inter-action forms the structure of modules that function as intelligent agents. Below, we will attempt to argue this definition even further.

2.2 The Structure of the Module Arises from Information

It is argued that meaning is usage [36]. I believe a more accurate perspective is that meaning is a function: something is used when its function is recognized because the function occurs before the usage. Equally accurate is the notion that the structure arises from information, and not the structure arises from usage [36]. We discuss these two aphorisms about the concept of the module in living organisms. When conceptualizing a module as a system, we refer to its definition [37]: a system is a community of elements that interact with one another.

This definition lays the groundwork for solving the problem of what elements of a system interact with each other. For example, what does an enzyme do to recognize a substrate, or what does a substrate do to recognize an enzyme? Certainly, there is recognition, and for this recognition, chemists publish a specialized journal titled "Molecular Recognition". Thus, we must accept that the structure of the module is born primarily from molecular recognition, meaning from information. Rightfully so, molecular recognition and self-organization are considered two main characteristics of molecules [38]. It is a well-known idea that a module can and should be analyzed, on one hand, as a structure and, on the other hand, as a function [39]. From the structural perspective, a module is a community of molecules, cellular elements or cells, individuals of the same species, or individuals of different species, whose interactions perform a function or form an effector that executes a function.

Let us analyze a molecular community, such as a group of ATP or GTP molecules. Both molecules are considered universal energy coins. During evolution, they specialized in two directions. In cells that use more energy, ATP molecules have an ad-vantage because their formation has a lower cost, whereas in cells specialized for signaling, GTP molecules are mainly used, even though the latter has a higher formation cost due to the G-C binding having three hydrogen bonds compared to the two in A-T and A-U bindings. In a previous study [40], it has been shown that genes are also modules, specifically genetic modules.

What is the structure of genetic or epigenetic modules? I do not think the structure of genetic modules can be identified solely by a fragment of nucleic acids. The same can be said for complex neural modules often identified with the term "memes" by R. Dawkins [41]. If genes and memes are modules with effector chemical modules such as the groups of ATP and DTP molecules or as the function of an allosteric enzyme, they are considered modules without effectors [42]. What we know today about the structure of modules is that their formation is a result of self- organizing processes [8, 38,43, 44]. By self-organization, we imply the interactions of elements at the lowest level of a system, from which emerges a global behavior at the highest level of this system [21]. From this perspective, the question arises of how the function of the module mani-fests in a way that acts as an intelligent agent and why modules are real intelligent agents.

2.3 Module as an Intelligent Agent or Decision-Maker

Today, scientific thought supports the idea that modules in the living world are formed by self- organizing processes or more precisely by self-organizing selective processes. From this, we can write that modules are formed through self-organization, where the term "module" (M) implies the term "self-organization" (SO). About a decade ago, in a study [45], it was argued that self-organization, which, as mentioned above, arises from self-organizing processes, is a process similar to human decision-making. According to these authors, the similarity in words is the result of using the same mathematical formulation belonging to probabilistic methods:

- - Self-organization is the process of evaluating the probabilities of states in a system in search of a more thermodynamically stable state.
- - Decision-making is the process of evaluating alternatives (states) of decision-making in search of the most stable preferential alternative.

From these claims, we conclude that self-organization can be considered decision-making (SO is DM), and decision-making can be considered self-organization (DM is SO). If the axiom of transitivity is to be used, we can assume that when the formation of modules (D) implies self-organization (SO) and self-organization implies decision-making (DM), then the formation of modules (D) can be considered decision-making (DM). It should be emphasized that decision-making is much more complex: several agents are involved in a decision. Thus, it remains to be accepted that each module is formed and behaves as an intelligent agent. As an intelligent agent, the module is defined in the functional perspective:

A module, much like an intelligent agent (A) perceives and stores information about the object (O) it needs to act upon, which we metaphorically call a lock. Thus, based on this information, the agent forms the effector (E), meaning the entirety that opens/unlocks the lock and in this way, the necessary function is performed. It should be emphasized that the formation of each module is not only a self-organizing process but also a selective one, and as such, the module does not always behave as a decision-maker or an intelligent agent.

In the first stage, intramodular selection occurs, meaning within the structure of the module, and in the second stage, intermodular selection occurs when the module interacts with other modules or with the environment. From this, we conclude that the classical variation-selection dyad [46] can be replaced by the dyad of intra- and inter-modular selection, which is in support of the idea of the marriage of self-organization with natural selection [47]. Before explaining the behavior of modules as intelligent agents, it is necessary to conceptualize these modules as real, not imaginary demons, from whose behavior semantic information is created.

2.4 Modular Thinking

Modules, just like coins, have two sides. On one side is the structure, and on the other is the function. Above, the definition of the module has been given in terms of both structure and function and now we need to understand and explain the origin and nature of the module simultaneously as both structure and function. Thinking about the module as both structure and function is like thinking popularly [48], thinking in terms of trees [49], selection thinking and is called modular thinking. Figure 2 illustrates the different types of modules belonging to the non-living world (A); the living world (B); the word module (C).

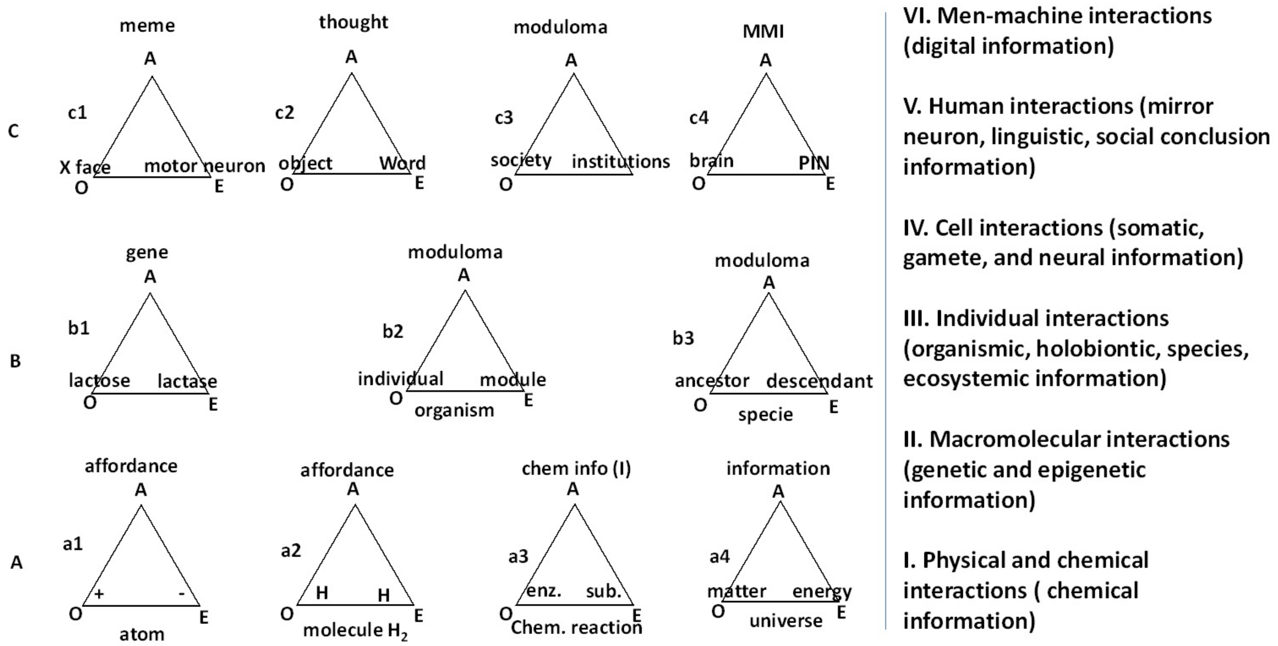

Figure 2: Types of Modules: Non-living world A: atom (a1), hydrogen molecule module (a2), enzyme/substrate module (a3), Universe (a4). B: Living module: genetic module (b1), organism module (b2), species module (b3). C: Immaterial world: neural module (c1), word module (c2), society module (c3), digital module (c4).

It should be emphasized that the behavior of modules as intelligent agents applies to every object, both as part of nature's inventory and as part of the list of artifacts. Therefore, an individual from the living world, a group of individuals belonging to a species, a language, a society, or one of its institutions, is considered a module, with the only difference being that the agent (A) in the aforementioned modules is referred to as a modulome (M). The modulome is the set of information possessed by an individual, a species, a language, a society, and so on.

In the concept of the universe as a module, it is shown that there exists information (I) according to which matter (M) can interact and organize, as well as a force, such as energy (E), that enables these interactions and organizations. This means that since the Big Bang, the evolution of matter has commenced, from physical-chemical and biological evolution to cultural evolution, which, within the modular concept, is understood as a continuous process of the modularization and energization of mat-ter.

As shown in Figure 2 (a4), the Universe, like any other module, behaves as an intelligent agent. Consequently, the universe and all modules can and should be viewed from a function and structure perspective. From the functional perspective, a module acts or behaves as an intelligent agent. The probability of a module performing a given function is determined by the information it possesses. Based on this, two formulas have been proposed for calculating this type of information, referred to as semantic information (is). If the probability of a module performing a function is less than or equal to 0.5, the formula used is: is = log (p), where p is the probability of performing the function. When the probability is greater than 0.5, the formula used is: is = 1 + (1 - log (p)).

Just like a coin, modules also have another side, which is their structure. From a structural perspective, modules are composed of assemblies of molecules, macro-molecules, cells, and cellular structures, individuals of the same species, or different species, whose interactions, because of the interaction information with both the internal and external environment, perform a function or create an effector that carries out a function. This definition of modules implies the consideration of various forms of interaction, each associated with its respective structural information.

We consider that six forms of interaction information operate: physic-chemical interactions (physic-chemical information); macromolecular interactions (genetic and epigenetic information); cellular interactions (somatic, gametic, and neural cellular information); non-human individual interactions (organismic, species-specific, and interspecies information); human individual interactions (neuronal, mirror neuron, gestural, linguistic, social, and cultural information); and human–machine interactions (digital information) (Fig. 2).

It is interesting to explain the similarity between the universal module and the digital module. Just as matter in the universe is expected to modularize over time, so too the brain is expected to modularize into immaterial modules. An example of this can be found in the digital module, which emerges from Man-Machine Information (MMI), as an intelligent agent.

On the other hand, we emphasize two forms of functional or semantic information that arise from the interactions of modules, which are semantic information in both material and immaterial forms. The analysis of modules simultaneously as structure and function corresponds to explanations of ultimate and proximate causation, or, in other words, to the respective answers to the questions 'How' and 'Why' [50].

Lastly, modular analysis corresponds with quantum thinking. Quantum thinking is the mind's ability to analyze a phenomenon or process from two perspectives simultaneously, just as modular thinking studies a module both as a structure and as a function. Similarly, to the values of quantum information, the values of semantic information are neither 0 nor 1, nor deterministic or discrete. This non-discrete and non-deterministic nature is reflected in the formulas used to compute semantic in-formation.

3 The Modular Evolution Model

3.1 Evolutionary Factors and Model Description

The study presented here does not support the idea that changes in allele frequencies within populations, driven by natural selection, mutations, migrations, or genetic drift, play a fundamental role in macroevolutionary transformations, especially when addressing concepts of universal evolution. For instance, while the role of natural selection is not questioned, its force is not primarily manifested in the well-known variation–selection dyad, but rather in the dyad of self-organization–selection. This reflects what S. Kauffman (1993) [20] describes as the 'marriage of selection and self-organization'.

In this dyad, the action of natural selection unfolds in two stages. In the first stage, selection operates on the structure of modules, whether they are material or immaterial systems. This process favors those systems, i.e., those modular structures, that are thermodynamically more stable. In the second stage, selection acts upon a specific object, which is always a module, and upon the function carried out by that same module. It is important to emphasize that within the modular concept, there is no need to debate the issue of multilevel selection [50] since modules are the only units of selection that are formed across different levels of biological organization.

Besides natural selection and self-organization, the three other factors of evolution are the three categories of the universe: matter, energy, and information. It is reasonable to accept the three categories of the universe as factors of evolution, because we believe that forces enabling the formation of modules play such a role. Moreover, when discussing evolution, time and its arrow serve as guiding principles for all other factors involved in the formation of modules. From the interconnections among the five factors just mentioned, and their relationship with time, the Modular Evolution Model has been constructed (Fig. 3) [11].

In this figure, the increasing values of the factors matter (M), energy (E), information (I), natural selection (NS), and self-organization (SO) are indicated by arrows along the four edges of the square as well as along its diagonal. In the latter case, the arrow of time (t) simultaneously represents the value of semantic information (I) of all modules within a material object, both living and non-living, as well as within an immaterial or physical system. The position of every material object and every immaterial system lies at a point along the arrow of time or along the diagonal that represents the value of semantic information. The model constructed as described above allows us to recognize the interconnections among these factors along the arrow of time. Thus, the increase in energy cor-responds to an increase in information and self-organization, but to a decrease in matter over time. On the other hand, the model shows that the rise in self-organization processes (SO), which reflect the percentage of modules formed, is accompanied by a decrease in the value of natural selection (NS), which reflects the percentage of modules eliminated. We denote with X the position in the arrow of time (t) of an object such as the hydrogen molecule, a gene module, a species module, etc., or an immaterial or mental system, such as a sentence module, a natural language module, a human society, and so on. By drawing perpendiculars from point X to the upper and lower edges of the square, we obtain two similar triangles: XAB and XA, B. Based on the similarity of the triangles XAB and XA, B, we can write:

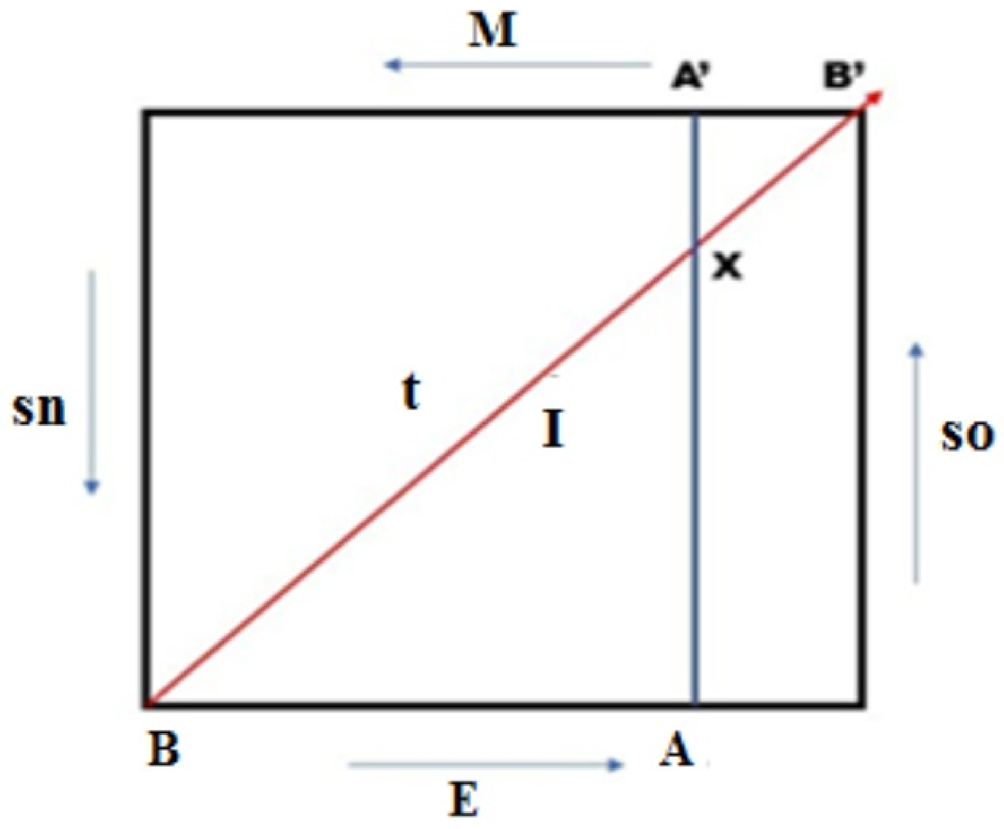

Figure 3: The Modular Evolution Model. Energy (E), matter (M), information (I), natural selection (NS), self-organization (SO), and their interconnections, along with the arrow of time (t).

$$AB/A'B' = XB/XB' = XA/XA' \tag{1}$$

or E/M = $i_p/i_f = t_0/t_1 = so/sn$.
It should be noted that i_p and to represent, respectively, the values of information and time before the emergence of the module, while if and t1 represent the values of information and time after the module has emerged. As shown in equation (1), the value of the ratio i_p / i_f is equal to the value of the ratio t_0 / t_1:

$$i_p/i_f = t_0/t_1 = i \tag{2}$$
$$\tag{3}$$

This means that, instead of the information ratio i_p / i_f, we can use the ratio t_0 / t_1, which is approximately known. For example, if life emerged around four billion years ago and that the earliest known fossil of a living organism dates back to approximately 3.8 billion years, we can calculate the value of i because t_0 = 200,000,000 and t_1 = 3,800,000,000; we find that i = 200,000,000 / 3,800,000,000 = 0.05. Based on equations (1) and (2), we can write:

$$E/M = i \tag{4}$$

or E = Mi. The similarity of this equation to Einstein's formula is both clear and conceptually significant.

3.2 What does the equation E = Mi indicate?

The Modular Evolution Model and the equation derived from it enable that every material object as part of the inventory of nature and every immaterial or mental system can and should be interpreted in an inseparable connection of the three categories of the universe. The advantages of the model and its associated equation are best demonstrated through their concrete applications. Almost a century ago, L. Lapicque [51] found that the excitation of the muscles in the mollusk *Aplysia sp.* requires 703 ergs of energy, whereas the excitation of the muscles in the amphibian Rana esculenta requires 508 ergs. Thus, the energy required for muscle excitation in the species *Aplysia sp.* and *Rana sp.* is, respectively, E Aplysia = 703 erg and E Rana = 508 erg. This means that, for the same excitation, the less-evolved mollusk Aplysia must expend approximately 1.3 times more energy than the amphibian Rana. Based on equation (2), we find that the value of i for the species Aplysia, which appeared approximately 530 million years ago, is t_0 / t_1 = 3,470,000,000 / 530,000,000 = 6, whereas, for the species Rana, which emerged around 350 million years ago, t_0 / t_1 = 3,650,000,000 / 350,000,000 = 14.

Thus, i Aplysia = 6 and i Rana = 14.

This means that the amphibian Rana, which is more evolutionarily advanced than the mollusk Aplysia, uses or contains more than twice as much information.

From formula (3), where E = Mi or M = E/i we find that: M Aplysia = 703/6 = 117g and M Rana = 518/14 = 37g. From these simple calculations, it follows that a mollusk that appeared earlier than an amphibian needs to use more than three times the mass. This fact indicates that, throughout evolution, a greater amount of information reduces the mass required to perform a given function. This fact contradicts the commonly accepted equality that ΔM is equal to ΔE, since ΔE = ΔM only when considering objects that belong approximately to the same period and have nearly the same value as i.

Nearly a century ago, it was observed that the formation of a helium atom from four hydrogen atoms was accompanied by a loss of 0.744% of its mass. The author of this study [52] attributed this phenomenon to electromagnetic origins. Perhaps the loss of mass may be explained by the gain of information associated with the formation of chemical bonds.

If chemical evolution reached an energetic potential with heavy metals, thanks to the formation of numerous chemical bonds, biological evolution also attained this peak with humans. This is considered an energetic paradox [53] made possible through linguistic, social, and cultural interactions. In both forms of evolution, we observe an increase in energy and the accumulation of information; as a result, evolution should be seen as the process of modularization and energization of matter.

3.3 Modular autonomy

The model of modular evolution, along with formula E = Mi provides us with a conceptual framework to recognize how the autonomy of three forms of systems can be created and maintained across non-living material modules, living ones, and non-material or mental modules.

It is a fact that a sentence is uttered or written only when its meaning is known in advance. This also applies to all other modules, ranging from molecules to complex neural modules. Thus, the action of the agent within a module emerges when three worlds are inseparably linked: the world of the elements that constitute the matter expected to be modularized, the world of information, and the world of effectors, which channels the energy of these elements.

In the language of mathematical theory of categories, we are dealing with a collection of objects, namely matter, energy, and information, and a set of morphisms, which depict metaphorically the arrows that point to the source and the object. The composition of morphisms in our case originates from matter as the source, and their target is the world of information and the world of energy. We do not know the mathematical theory of categories; hence, we are, unfortunately, deprived of a potentially correct and elegant explanation, and are therefore compelled to seek other approaches.

Specifically, we must hypothesize that the connections or interactions between system elements as modules are simultaneously a consequence of information and a cause of the energy that forms the effectors. Such numerous systems exist, but their fate is in the hands of natural selection. Autonomy can be attained only by those systems where information in the form of connections for organizations matches energy in the form of those connections that produce energy.

We mention the presence of ATP and GTP molecules in the cell environment as an example. Both molecular types provide energy, but GTP is more "costly" due to its involvement in three hydrogen bonds, which is offset by its specialized role in cellular regulatory processes.

We believe that this molecular behavior is not rare and that selection has made it possible to create optimal modules. Regardless of the misconception of predation (predatory information) (!?), which suggests that living systems steal information from the outside, P. Lherminier [54] offers an interesting perspective when he proposes that each species represents a unique solution to the equation that balances information gain with energy/mass.

This idea supports formula i = E/M because it does not comply with the equation ΔE = ΔM of the formula E = mc^2. On the other hand, it indicates that modular autonomy is attained only when each value of i corresponds to a certain ratio E/M.

3.4 The value of i and major evolutionary transitions

Some authors [40] were the first to underline that the genetic distances between taxa can be converted into absolute geological time. Even in formula E = Mi, the value of i represents not only the ratio of time before and after the emergence of a taxon, but is also converted as a ratio of information before and after the emergence of the taxon, which is reflected in formula (2) where $i_p/i_f = t_0/t_1 = i$. Table 1 demonstrates that each evolutionary event or transition occurring at a certain time is associated with a corresponding value of i and t.

It can be observed that the doubling, or theoretical twofold increase, of information (from 1, 2, 4, 8, 16, etc.) almost coincides with the values of t in the formula $t = t_0/t_1$, where t_0 and t_1 represent the time before and after the occurrence of the event.

Thus, it is noted that the tempo of evolution is higher in the later stages of evolutionary history, where the correspondence between the values of I and t is also greater. Interestingly, the doubling of information from 1 (in eukaryotes) to 2 (in multicellular organisms) requires a longer time interval. This fact helps explain why we should not be surprised by the Cambrian Explosion, since in this case as well a longer time span was necessary.

No	Evolutionary events	Timeline	Value of i, ideal and factual (in parentheses)
1	The first fossils (Archaea)	4 milliards	- -
2	Eukaryotic cells	2 milliards	2 (1)
3	Multicellular organisms (Holozoa)	1 milliard	4 (3)
4	Cambrian explosion (Vertebrata)	500 million	8 (7)
5	Mammalia	250 million	16 (15)
6	Flowering plants and placental mammals	120 million	32 (26)
7	Haplorrhini	60 million	64 (65)
8	Catarrhini	30 million	128 (132)
9	Hominidae	15 million	256 (265)
10	Bipedalism	7.2 million	512 (532)
12	?	4 million	1024 (994)
13	Homo erectus	2 million	2048 (1996)
14	?	1 million	4096 (3999)
15	?	500 000	8192 (7771)
16	Homo sapiens	250 000	16384 (16041)
17	Language	125 000	33768 (32007)
18	?	62 000	67536 (64505)
19	?	31 000	135072 (129030)
20	Mesolithic	16 000	270144 (245061)
21	Neolithic Revolution	8000	542288 (499991)
22	Yamnaya	4000	1 084 576 (999991)
23	Christianity	2000	2 169 152 (1999994)
24	?	1000	4 320 354 (3999991)
25	European Renaissance	1500	8 640 708 (7999999)
26	Industrial Revolution	250	17 281 416 (16 399 999)
27	Postmodern period	Nowadays	34 562 832

Table 1: Evolutionary events and values of i and t.

The data in Table 1 support the fact that there is no effect of geographical isolation on the rate of speciation as well as the idea that speciation and extinction follow a scaling law, where new taxa have a faster rate [55]. It is well known that geometric progression is characterized by slow growth in the early stages and rapid growth in the later stages. This pattern is also observed in the geometric series corresponding to major events in biological evolution. This observation supports the modular evolution model in relation to time, information, energy, and matter. From the coincidence of the doubling of the value of i with a major evolutionary event, we can assume that a significant change in biological evolution must have occurred between the emergence of multicellular organisms and the Cambrian Explosion (Table 1). As shown, the theoretical and actual values of i do not align in the Cambrian Explosion, which remains equally unknown in nowadays paradigm. Equally significant is the consistency of the value of "i" for events during cultural evolution. Such similarities likely occurred even after the appearance of the genus Homo and the species within this genus.

3.5 Species are modules

Species are not merely nominal units or modules of words like natural objects and man-made artifacts. Rather, they are biological modules, genuine functional units of nature, and concrete living units. We evidenced this fact in the concept of the uni-verse as a module (Fig. 2) where three interacting worlds are identified: the world of information (I) concerning matter as a world that will be modularized (M), and the world of effectors as energy (E).

In the case of species, their stability, persistence, or autonomy is achieved when the mass value of the ancestors is equated with the energy value expressed by the descendants as effectors. According to the formula E = Mi, this balance of the ancestors' mass with the energy, such as the descendants of a species as effectors, is ensured by the value of i, which represents the ratio between the amount of information before and after the emergence of the taxon.

Thus, there is a real mass-energy equivalence, which is given in the formula E = m c^2, but this equivalence is ensured by information.

It is established that the value of i for each species does not change over time. The sole species that makes an exception is Homo sapiens, and in this regard the man is considered an energy paradox [53]. This occurs because the information about the species to which we belong accumulates over time. Consequently, the requirements for life or our niches have changed completely between nowadays man and those of the pre-industrial revolution, the Neolithic period, or the earliest human populations. Variations observed between human populations over time support the notion that information regulates and balances the mass of an autonomous or persistent object with the energy required to sustain its stability.

The formula E = Mi helps us to explain this energetic paradox. There is a fact that today's energy of the human society with eight billion inhabitants has increased 115 times compared to the energy of the human society 500 years ago, approximately during the European Renaissance [56].

The values of i and t are 500 years ago and today are 8640708 and 34 562 832, respectively (Table 1).

Accepting the inhabitants' number of the respective periods (500 million and 8 billion) as a matter, employing the formula E = mi, we find that the difference is 70 times and not 115 times. However, this fact supports the modular evolution model and the E = Mi formula since they must account for the accumulation of errors in time estimation.

Moreover, it is interesting to point out that the only discrepancy between the theoretical and actual value of i in Table 1 is that of 500 million years ago, where the actual value has quadrupled.

3.6 The general meaning of the Modular Evolution Model

The modular evolution model and the formula E = Mi derived from it to illustrate how matter undergoes modularization and energization over time, creating a conceptual framework for us to speculate on why and when the Big Bang might occur. The widely accepted idea that the Big Bang originated from a point of unimaginable density and heat supports the notion that the cause of this explosion was the uni-verse reaching a state of maximum potential energy, similar to the position of a pendulum at its highest point. Just as the pendulum at its peak has maximum gravitational potential energy, the universe reaches a state of extraordinary potential energy when its information and energy values are at their peak, while its matter or mass is at a minimum (Fig. 2, a4).

This is also demonstrated by the concept of the universe as a module, as shown in Fig. 2, a4, where information (I), energy (E), and matter (M) take on the roles of intelligent agent (A), effector (E), and object (O), respectively. As in any module, in this case, energy, as the effector of the universe, is considered a key shaped by the in-formation gathered about matter, which acts as the lock. The action performed, which leads to the creation of a physical entity like a hydrogen molecule or a function like that of a genetic module, reflects the correspondence between matter and energy based on the information that structures the molecule or gene through self-organizing selection processes. It is important to highlight that by self-organizing selection processes, we mean the way physical units and modules are formed through information and how they are either favored or eliminated through selection in both the living and non-living worlds.

From this perspective, not only the species discussed by P. Lherminier [54] but every other module, including the species itself, makes sense. Each module demonstrates how the expenditure of energy/matter is balanced with the gain of information. This means that the preservation of a physical identity, such as a quantum, atom, molecule, or any module in the living world, is a result of an energy/matter ratio at a given moment. Therefore, the key-lock relationship can be understood as an energy/matter match. But here, a conceptual obstacle is encountered, and a paradigmatic change is required.

Energy emerges from interactions. Apples falling from a tree represent an interaction, resulting in gravitational potential energy. Similarly, the enzyme/substrate bond is another type of interaction, but here we are dealing with chemical potential energy rather than gravitational potential energy. The issue arises naturally. Knowledge or steric information is not included in the equation $E = mc^2$. This leads us to question why we look for the cause of the existence of "demons" outside of matter; in reality, demons are embedded within matter itself, appearing as its properties, including information and energy. The issue is resolved by embracing the view of J. Roederer [58] who proposed that interactions can be categorized into two groups: force-based interactions, which involve gravitational and elastic energy, and information-based interactions. The formula $E = mc^2$ is based solely on force-based interactions and indicates kinetic energy by the fact that it links mass/energy to velocity. While formula $E = M$ can be seen as representing the potential energy.

The formula $E = mc^2$ is based solely on force-based interactions. Let us mention a fact. Chemical energy is regarded as chemical potential energy, and it is rightly accepted that the source of this energy lies in the energy of chemical bonds.

Why are chemical bonds not considered a form of interaction information? Why is steric information in enzyme/substrate binding or other physicochemical properties ignored? As stated earlier, it can be accepted that interactions are a result of information, and energy arises from the interactions that enable information. Therefore, we must accept that the evolutionary connections between energy, matter, and in-formation are incomplete unless we recognize information-based interactions. On the other hand, we must acknowledge that there is no direct equivalence between the three categories of the universe; instead, there are fixed relationships over time. Therefore, these are evolutionary connections, not merely physical ones. For instance, there can be no equivalence between information or energy and matter, nor can one be substituted for the other.

The question arises: Why is the Big Bang expected to occur at a time when the values of information and energy are at their maximum? Let us revisit Fig. 3 and compare, on one hand, the maximum values of information and energy, and on the other, the decrease in mass. As explained earlier, information and energy, as measurable properties, are inseparable from each other. If information enables interactions, which are considered outcomes of information, some of these interactions directly generate energy, especially when information is linked to the organization of both material and non-material systems. Naturally, interactions based on information do not exclude those based on force, from which the remaining energy also arises. In-formation, as a factor in the organization of matter, plays a role in the formation of this energy as well. Just as we recognize the potential energy generated by gravity, which arises from force-based interactions, we must also acknowledge the potential energy created by information, which arises from information-based interactions.

Finally, the question arises: What might the scenario of the connections between the three categories of the universe; energy, matter, and information, over time, look like?

Immediately after the Big Bang, kinetic energy emerges as the ability of matter evolves, and, like a pendulum, the maximum potential energy is once again reached. This cycle repeats, illustrating why matter is always in motion and active. Our idea of the universe's infinity manifested through cyclic repetitions precisely at the time when information and energy peak while matter reaches its smallest mass, finds resonance in the cosmological model of aeon proposed by the Nobel laureate R. Penrose [59]. Similarly, Penrose's view is that there is no fundamental difference between an infinitely large universe composed of countless photons and an infinitely small universe composed of a single photon, highlighting their shared intelligent agent's behavior. Atom or molecule modules behave the same as a genetic or linguistic module, and so does the universe itself.

The Big Bang hypothesis gives us the confidence to offer an opinion on dark matter and dark energy, which we view as unenergized and energized matter, respectively. First, we find confidence in the evolution of the categories of the universe. There is no doubt that, throughout evolution, information and energy have undergone changes. To see this, one only needs to observe the various forms of information, interaction, and energy that have emerged along the arrow of time. It becomes clear that matter has also changed over time. This change may be reflected in its composition as an active and inactive matter. Secondly, we find confidence in the almost complementary relationship between dark matter (22.7 - 26.8%) and dark energy (68.2 - 72.8%). We believe that dark matter represents inactive matter, which does not interact due to the lack of information necessary for the self-organizing selection processes that give rise to physical units of interaction and modules. The remaining percentage of matter (4.5 – 4.9%) is likely an intermediate state of matter. On the other hand, dark energy can be considered as an energized matter. Energized matter refers to that which has currently emerged in the universe as physical units of interaction or as biological, linguistic, and socio-cultural modules.

4 Universal evolution is modular

Table 2 compares some evolutionary principles from the perspectives of the Modern Synthesis (MS), the Extended Evolutionary Synthesis (EES), and Modular Evolution (ME).
Accepting the concept of modularity as a general organizing principle that applies to the non-living, living world as well as the non-material world, the Theory of Modular Evolution has an advantage over the Standard Theory of Evolution and the Theory of Extended Evolutionary Synthesis because it provides arguments that indicate that universal evolution is modular.

No	Phenomena	Theories		
		MS	EES	ME
1	Inheritance and information	In the living world, there are two systems of inheritance - genetic inheritance and socio-cultural inheritance, and two corresponding forms of information: genetic and non-genetic information.	There are four inheritance systems: the genetic, epigenetic, behavioural, and symbolic inheritance systems, and two forms of information: genetic and epigenetic.	The number of inheritance systems corresponds to the number of information systems, according to which modules are formed, giving rise to forms of interaction information, and material and non-material semantic information.
2	Variations	The source of variations is random and undirected mutations.	Besides mutations, variations arise as directed developmental trends	Variations are variants of modules characterized by different structures, mainly shaped by the organization itself and by another similar process called Assembly.
3	Natural selection	Selection occurs through interaction with the environment according to the variation/selection dyad	Idem	The selection occurs in two stages: first, during the formation of the module structures, and second, through the interaction of these modules with the environment, according to the dyad self-organization/selection or assembly/selection.
4	The factors of evolution and macroevolution	The factors of evolution are those that change the genetic composition of the population (mutations, natural selection, migrations, genetic drift) and macroevolution is a continuation of microevolution.	Idem	The factors of evolution are those that alter the genetic composition of a population, but also those involved in the formation of modules such as matter, energy, information, self-organization, and natural selection, to which macroevolution is linked. Macroevolutionary drives such as speciation processes or major evolutionary transitions occur in compliance with the value increase of i in the formula $E = Mi$
5	Causation	There is historical, phylogenetic, or ultimate causation, and current, developmental, or proximate causation.	Idem	Ultimate causation refers to the formation of the module's structure in the past based on information, while proximate or current causation concerns the performance of the function by effectors as energy.

Table 2: Comparison of some evolutionary principles from the perspective of the Modern Synthesis (MS), the Extended Evolutionary Synthesis (EES), and Modular Evolution (ME).

In the modular concept, this statement suggests that matter's capacity for stability or static persistence arises in the non-living world, starting with atoms at the very least. This happens when the environment, serving as a carrier of specific information, facilitates the equivalence of mass and energy.

This idea can be considered correct if we accept that the origin of the living world involves the formation of three interacting realms: the world of information as an intelligent agent (A), the world of effectors (E) and the world of objects (O), constitute the inventory of nature, where unlike the non-living world certain information has been internalized.

Just as the electro-magnetic field achieves balanced control over oppositely charged particles within an atom, so does a fragment of nucleic acids, acting as the intelligent agent (A), regulate the balance between the energy of the effectors (E) and the mass of the objects (O).

Another advantage of Modular Evolution over the two prevailing theories is that it recognizes natural selection as operating in two distinct stages, highlighting its non-random behavior and creative nature. This helps explain why modules serve as objects of natural selection and why evolutionary factors are the ones that contribute to their formation. The theory of Modular Evolution makes it possible to explain how undesigned or unplanned actions and reactions give rise to purposeful behaviors. This includes both the static persistence of objects, such as the formation of minerals, and the performance of proper function in living organisms, such as the removal of paramecia from an acidic environment. In both cases, we are talking about the emergence of material semantic information, which today is still considered taboo in the evolution of material systems.

The advantages of Modular Evolution Theory (MET) in comparison to Modern Synthesis and Extended Evolutionary Theory are related to the mechanism by which modules acquire and maintain autonomy and the ability to for stability and evolvability. In favor of this autonomy is the Common Cause Principle. Reichenbach's Common Cause Principle is the claim that if two events are correlated, then there is either a causal connection between the correlated events that is responsible for the correlation, or there is a third event that brings about the correlation [46]. Therefore, as shown in Fig. 1 /1d, the common cause of both Energy (E) and Information (I) is Matter (M).

From our perspective, matter is the common cause of its dual properties: energy and information. Like chemical bonds, it is the same property of matter that allows it to both store information and produce energy. Additionally, Reality Criteria (RC) is a special case of the Common Cause Principle (CCP): if, without in any way disturbing, a system, we can predict with certainty (i.e probability equal to unite) the value of a physical quantity, then there exist elements of reality corresponding to that quantity [60]. In our opinion, this element of reality is information in the form of a chemical bond and could be included in the Einstein-Podolsky-Rosen criteria.

Both Common Cause and Reality Criteria (The Einstein-Podolsky-Rosen) find sup-port in the intelligent agent idea, as the information accumulated by the matter, soon to be modularized, is the same that generates energy. On the other hand, like the Category Theory (CT) in mathematics, which is not focused on objects' elements [61] the Modular Evolution Theory also studies objects as a set of system elements.

Additionally, self-organizing selective processes are part of a shorter computer pro-gram [62] a metaphor for the Universe as a gigantic computer [63]. Finally, modules must also be seen in ontological, epistemological, and methodological assumptions. Orthology is defined as the study of being and the nature of reality [64], in contrast to epistemology, it is an approach to understanding how we come to know things and what we should know.

From these two perspectives, module-focused studies should be considered a valid orientation in scientific research methods. By incorporating information into the history of matter, it highlights the universal nature of chemical, biological, and cultural evolution. As a result, the life sciences returned to the study of matter, much like their sister disciplines, chemistry and physics.

5 Conclusions

- 1. The Theory of Modular Evolution is founded on the concept that both energy and information are properties of matter.
- 2. Modules, as objects of natural selection, are primarily formed through the process of self-organization and undergo natural selection in two stages: first, during their formation, and second, during the performance of their function.

- 3. The factors of evolution are those that contribute to the formation of modules, including matter, energy, information, natural selection, and self-organization. The factors of evolution form an evolutionary relationship among one another, expressed through the equation E = Mi.
- 4. The mechanism of evolution is the formation of modules that behave as intelligent agents, leading to the creation of objects that are part of the inventory of nature, artifacts, and mental systems created by man. In any case, this mechanism operates when the energy of the effectors (E) guided by the information (A) of this mass achieves a balance with that mass (O), resulting in evolutionary change.
- 5. Through this mechanism, we can explain how undesigned or unplanned actions and reactions give rise to purposeful behaviors. This includes both the static persistence of atoms and minerals, as well as the performance of specific functions, such as the removal of paramecia from an acidic environment.
- 6. Species are modules, real-life units. The persistence of species as material systems is made possible because, at a given point in time, the mass of their ancestors was balanced with the energy generated by the descendants as effectors through the provided information. If we recall the full title of Charles Darwin's major work (1859), The Origin of Species by Means of Natural Selection, or the Preservation of Favored Races in the Struggle for Life, we understand that the mechanism of evolution is, on the one hand, the pressure of selection, and on the other hand, equally important, the mechanism of species stability.

To paraphrase T. Dobzhansky, it can be said that just as nothing in biology makes sense except in the light of evolution, so nothing in evolution makes sense except in the light of information.

References

[1] Landauer, R. Irreversibility and Heat Generation in the Computing Process. IBM J. Res. Dev. 1961, 5, 183–191, doi:10.1147/rd.53.0183.

[2] Shannon, C. A Mathematical Theory of Communication. The Bell System of Technical Journal 1948, 27, 379–423.

[3] Lehn, J.-M. Toward Complex Matter: Supramolecular Chemistry and Self-Organization. Proc. Natl. Acad. Sci. U. S. A. 2002, 99, 4763–4768, doi:10.1073/pnas.072065599.

[4] Gershenson, C.; Fernández, N. Complexity and Information: Measuring Emergence, Self-Organization, and Homeostasis at Multiple Scales. Complexity 2012, 18, 29–44, doi:10.1002/cplx.21424.

[5] Frank, S.A. Natural Selection. V. How to Read the Fundamental Equations of Evolutionary Change in Terms of Information Theory. J. Evol. Biol. 2012, 25, 2377–2396, doi:10.1111/jeb.12010.

[6] Menant, C. Information and Meaning. Entropy 2003, 5, 193–204, doi:10.3390/e5020193.

[7] Krzanowski, R. What Is Physical Information? Philosophies 2020, 5, 10, doi:10.3390/philosophies5020010.

[8] Haken, H.; Portugali, J. Information and Self-Organization. Entropy 2017, 19, 18, doi:10.3390/e19010018.

[9] Spirkin, A.G. Dialectical Materialism; Progress Publishers: Moscow, 1983.

[10] Bajrami, Z. Informacioni dhe evolucioni modular; Akademia e Shkencave te Shqiperise, 2024.

[11] Bajrami, Z. Information and Modular Evolution 2024.

[12] Von Bertalanffy, L. General System Theory: Foundations, Development, Applications; New Paperback, 1969.

[13] Stonier, T. Information and the Internal Structure of the Universe; Springer-Verlag, 1990.

[14] Stonier, T. Information as a Basic Property of the Universe. Biosystems 1996, 38, 135–140, doi:10.1016/0303-2647(96)88368-7.

[15] Hartwell, L.H.; Hopfield, J.J.; Leibler, S.; Murray, A.W. From Molecular to Modular Cell Biology. Nature 1999, 402, C47-52, doi:10.1038/35011540.

[16] Fodor, J. The Modularity of Mind: An Essay on Faculty Psychology; MIT Press: Cambridge, MA, 1983.

[17] Barkow, J.; Cosmides, L.; Tooby, J. The Adapted Mind: Evolutionary Psychology and the Generation of Culture; Oxford University Press, 1992.

[18] Armstrong, D.F.; Wilcox, S.E. The Gestural Origin of Language; Oxford University Press, 2007.

[19] Newman, M.E.J. Modularity and Community Structure in Networks. Proc. Natl. Acad. Sci. 2006, 103, 8577–8582, doi:10.1073/pnas.0601602103.

[20] Kauffman, S.A. The Origins of Order: Self-Organization and Selection in Evolution; Oxford University Press: New York, 1993; ISBN 978-0-19-507951-7.

[21] Self-Organization in Biological Systems; Camazine, S., Ed.; Princeton Univ. Press: Princeton, NJ, 2003; ISBN 978-0-691-11624-2.

[22] Sugita, M.; Onishi, I.; Irisa, M.; Yoshida, N.; Hirata, F. Molecular Recognition and Self-Organization in Life Phenomena Studied by a Statistical Mechanics of Molecular Liquids, the RISM/3D-RISM Theory. Molecules 2021, 26, 271, doi:10.3390/molecules26020271.

[23] Vopson, M.M. The Mass-Energy-Information Equivalence Principle. AIP Adv. 2019, 9, 095206, doi:10.1063/1.5123794.

[24] Menin, B.M. Theoretical Limits of the Mass–Energy–Information Equivalence. Eur. J. Sci. Innov. Technol. 2025, 5, 223–236.

[25] Ottinger, H. Philosophical Approach to Quantum Field Theory; Cambridge University Press, 2017.

[26] Deutsch, D.; Marletto, C. Constructor Theory of Information. Proc. R. Soc. A 2015, 471, 20140540, doi:10.1098/rspa.2014.0540.

[27] Dobzhansky, T. Nothing in Biology Makes Sense except in the Light of Evolution. American Biology Teacher 1973, 35, 125–129, doi:10.2307/4444260.

[28] Marshall, S.M.; et al. Identifying Molecules as Biosignatures with Assembly Theory and Mass Spectrometry. Nat. Commun. 2021, 12, 3033, doi:10.1038/s41467-021-23258-x.

[29] Sharma, A.; et al. Assembly Theory Explains and Quantifies Selection and Evolution. Nature 2023, 622, 321–328, doi:10.1038/s41586-023-06600-9.

[30] Lloyd, S.; Mohseni, M.; Rebentrost, P. Quantum Algorithms for Supervised and Unsupervised Machine Learning. arXiv:1307.0411, 2013.

[31] Schrödinger, E. What Is Life? & Mind and Matter; Cambridge University Press, 1974.

[32] Alemi, M. Life, Energy and Information. In The Amazing Journey of Reason; Springer, 2020; pp. 1–10. ISBN 978-3-030-25961-7.

[33] Lherminier, P. La prédation informative: vers un nouveau concept d'espèce. C. R. Biol. 2018, 341, 209–218.

[34] Bateson, G. Steps to an Ecology of Mind; University of Chicago Press, 2000; ISBN 978-0-226-03906-0.

[35] Shannon, C. A Mathematical Theory of Communication. 27, 379–423.

[36] Tomasello, M.; et al. Understanding and Sharing Intentions: The Origins of Cultural Cognition. Behav. Brain Sci. 2005, 28(5), 675–691.

[37] Von Bertalanffy, L. General System Theory: Foundations, Development, Applications. New Paperback, 1969. Available online: https://www.abebooks.com/9780807604533/General-System-Theory-Foundations-Development-0807604534/plp

[38] Modularity in Development and Evolution; Schlosser, G.; Wagner, G.P., Eds.; Univ. of Chicago Press: Chicago, 2004; ISBN 978-0-226-73853-6.

[39] Rebek Jr, J. Molecular Recognition with Model Systems. Angew. Chem. Int. Ed. 1990, 29(3), 245–255.

[40] Bajrami, Z. The Modular Concept of Gene. J. Nat. Sci. Res. 2013, 3, 125–130.

[41] Dawkins, R. The Selfish Gene: 40th Anniversary Edition; Oxford University Press: New York, 2016; ISBN 978-0-19-878860-7.

[42] Bajrami, Z. Informacioni dhe evolucioni modular; Akademia e Shkencave të Shqipërisë: Tiranë, 2024; ISBN 9789928809193.

[43] Wagner, G.P. Homologues, Natural Kinds and the Evolution of Modularity. Amer Zool 1996, 36, 36–43.

[44] Wagner, G.P.; Lynch, V.J. Evolutionary Novelties. Curr. Biol. 2010, 20, R48–52.

[45] Yukalov, V.I.; Sornette, D. Self-Organization in Complex Systems as Decision Making. Adv. Complex Syst. 2014, 17, 1450016, doi:10.1142/S0219525914500167.

[46] Forterre, P.I.P. Darwin's Goldmine Is Still Open: Variation and Selection Run the World. Front. Cell. Infect. Microbiol. 2012, 2.

[47] Kauffman, S.A. The Origins of Order; Oxford University Press: New York, 1993.

[48] Mayr, E. Evolution and Anthropology: A Centennial Appraisal; Washington, 1959.

[49] O'hara, R.J. Population Thinking and Tree Thinking in Systematics. Zool. Scripta 1997, 26, 323–329.

[50] Mayr, E. Cause and Effect in Biology. Science 1961, 134, 1501–1506, doi:10.1126/science.134.3489.1501.

[51] Sober, E. The Nature of Selection: Evolutionary Theory in Philosophical Focus; MIT Press, 1987.

[52] Lapicque, L. L'Excitabilité En Fonction Du Temps: La Chronaxie, Sa Signification et Sa Mesure; Presses Universitaires de France, 1926.

[53] Bethe, H.A. Energy Production in Stars. Phys. Rev. 1939, 55, 434–456, doi:10.1103/PhysRev.55.434.

[54] Pontzer, H.; et al. Constrained Total Energy Expenditure and Metabolic Adaptation to Physical Activity in Adult Humans. Curr. Biol. 2016, 26, 410–417, doi:10.1016/j.cub.2015.12.046.

[55] Lherminier, P. La prédation informative: vers un nouveau concept d'espèce. C. R. Biol. 2018, 341, 209–218, doi:10.1016/j.crvi.2018.02.004.

[56] Henao Diaz, L.F.; et al. Macroevolutionary Diversification Rates Show Time Dependency. Proc. Natl. Acad. Sci. 2019, 116, 7403–7408, doi:10.1073/pnas.1818058116.

[57] Harari, Y.N. Sapiens: História breve da humanidade; Elsinore, 2013.

[58] Sober, E. The Principle of the Common Cause. In Probability and Causality; Fetzer, J.H., Ed.; Springer: Dordrecht, 1988; pp. 211–228.

[59] Roederer, J.G. On the Concept of Information and Its Role in Nature. Entropy 2003, 5, 3–33, doi:10.3390/e5010003.

[60] Penrose, R. Cycles of Time: An Extraordinary New View of the Universe; Vintage, 2012.

[61] Bell, J.S. On the Einstein Podolsky Rosen Paradox. Physics 1964, 1, 195–200, doi:10.1103/PhysicsPhysiqueFizika.1.195.

[62] Simmons, H. An Introduction to Category Theory; Cambridge University Press, 2011; ISBN 978-1-107-01087-1.

[63] Kolmogorov, A. List of Conference Participants. J. Cult. Econ. 1995, 19, 95–101, doi:10.1007/BF01074199.

[64] Lloyd, S. Programming the Universe: A Quantum Computer Scientist Takes on the Cosmos; Knopf Doubleday, 2007; ISBN 1-4000-3386-1.

[65] Crotty, M. The Foundations of Social Research: Meaning and Perspective in the Research Process; Routledge, 2020; ISBN 978-1-00-311570-0.