

The World as Evolving Information

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Abstract. This philosophical paper discusses the benefits of describing the world as information, especially in the study of the evolution of life and cognition. Traditional studies encounter difficulties because it is difficult to describe life and cognition in terms of matter and energy, falling into a dualist trap. However, if matter and energy, as well as life and cognition, are described in terms of information, evolution can be described consistently as information becoming more complex. Moreover, information theory is already well established and formalized.

The paper presents five tentative laws of information, which are generalizations of Darwinian, cybernetic, thermodynamic, and complexity principles. These are further used to discuss the notions of life and cognition, including their origins and evolution.

1 Introduction

Throughout history we have used concepts from our current technology as metaphors to describe our world. Examples of this are the description of the body as a factory during the Industrial Age, and the description of the brain as a computer during the Information Age. These metaphors are useful because they extend the knowledge acquired by the scientific and technological developments to other areas, illuminating them from a novel perspective. For example, it is common to extend the particle metaphor used in physics to other domains, such as crowd dynamics [1]. Even when people are not particles and have very complicated behaviour, for the purposes of crowd dynamics they can be effectively described as particles, with the benefit that there is an established mathematical framework suitable for this description. Another example can be seen with cybernetics [2,3], where the system metaphor is used: everything is seen as a system with inputs, outputs, and a control that regulates the internal variables of the system under the influence of perturbations from its environment. Yet another example can be seen with the computational metaphor [4], where the universe can be modelled with simple discrete computational machines, such as cellular automata or Turing machines.

Having in mind that we are using metaphors, this paper proposes to extend the concept of information to describe the world: from elementary particles to galaxies, with everything in between, particularly life and cognition. There is no suggestion on the nature of reality as information [5]. This work only explores the advantages of *describing* the world as information. In other words, there are no ontological claims, only epistemological.

In the next section, the motivation of the paper is presented, followed by a section describing the notion of information to be used throughout the paper. In Section 4, tentative laws of information are put forward. These are applied to the notions of life (Section 5) and cognition (Section 6). The paper closes presenting future work and conclusions.

2 Why Information?

There is a great interest in the relationship between energy, matter, and information [6,7,8]. One of the main reasons for this arises because this relationship plays a central role in the definition of life: Hopfield [9] suggests that the difference between biological and physical systems is given by the meaningful information content of the former ones. Not that information is not present in physical systems, but—as Roederer puts it—information is *passive* in physics and *active* in biology [10]. However, it becomes complicated to describe how this information came to be in terms of the physical laws of matter and energy. In other words, it is not obvious to describe information in terms of physics, as it requires an *interpreter* to “decode” the information. In this paper the inverse approach is proposed: let us describe matter and energy in terms of information. If atoms, molecules and cells are described as information, there is no need of a *qualitative* shift (from non-living to living matter) while describing the origin and evolution of life: this is translated into a *quantitative* shift (from less complex to more complex information).

There is a similar problem when we study the origin and evolution of cognition [11]: it is not easy to describe cognitive systems in terms of matter and energy. The drawback with the physics-based approach to the studies of life and cognition is that it requires a new category, that in the best situations can be referred to as “emergent”. However, this is not an useful explanation. Moreover, it stealthily introduces a dualist view of the world: if we cannot relate properly matter and energy with life and cognition, we are forced to see these as separate categories. Once this breach is made, there is no clear way of studying or understanding how systems with life and cognition evolved from those without it. If we see matter and energy as particular, simple cases of information, the dualist trap is avoided by following a continuum in the evolution of the universe.

Another benefit of using information as a basic descriptor for our world is that the concept is well studied and formal methods have already been developed [12,13], as well as its philosophical implications have been discussed [14]. Thus, there is no need to develop a new formalism, since information theory is well established. I borrow this formalism and only interpret it in a new way.

Finally, information can be used to describe other formalisms: not only particles and waves, but also systems, networks, and agents can be seen as information. In other words, it can contain other descriptions of the world, potentially exploiting their own formalisms. In other words, it is an *inclusive* formalism.

3 What Is Information?

Extending the notion of Umwelt [15], the following notion of information can be given:

Notion 1. *Information is anything that an agent can perceive or sense.*

This can be applied to everything that surrounds us, including matter and energy, since we perceive it and we are agents, according to the following notion:

Notion 2. *An agent is a description of an entity that acts on its environment [16, p. 39].*

Noticing that agents (and their environments) are also information (as they can be perceived by other agents), an agent can be a human, a cell, a molecule, a computer program, an electron, a city, a market, an institution, or a star. Each of these can be described (by us) as *acting* in their

environment. However, not all information is an agent, e.g. temperature, color, velocity, hunger, profit.

Information will be relative to the agent perceiving it¹, and will only “exist” if there is an agent to perceive it, i.e. interacting with the information source. The *meaning* of the information will be given by the *use* the agent perceiving it makes of it [18]. This makes Notion 1 a *pragmatic* one.

Like this, an electron can be seen as an agent, which perceives other electrons as information. The same description can be used for molecules, cells, and animals. We can distinguish:

First order information is that which is perceived directly by an agent. For example, the information received by a molecule about another molecule

Second order information is that which is perceived by an agent about information perceived by another agent. For example, the information perceived by a human observer about a molecule receiving information about another molecule.

Most of the scientific descriptions about the world are second order information, as we perceive how agents perceive and produce information. The present approach also introduces naturally the role of the observer in science, since everything is “observing” the (limited, first order) information it interacts with from its own perspective. Humans would be second-level observers, observing the information observed by information.

Information is not necessarily conserved, i.e. it can be created (when an agent perceives it), destroyed (when no agent perceives it), or transformed (by an agent). *Computation* can be seen as the *change* in information, be it creation, destruction, or transformation. Matter and energy can be seen as particular types of information that cannot be created or destroyed, only transformed, along with the well-known properties that characterize them.

The amount of information required to describe a process, system, object, or agent determines its *complexity* [13]. According to our current knowledge, during the evolution of our universe there has been a shift from simple information towards more complex information [19] (the information of an atom is less complex than that of a molecule, than that of a cell, than that of a multicellular organism, etc.). This “arrow of complexity” [20] in evolution can guide us to explore general laws of information.

4 Tentative Laws of Information

Seeing the world as information allows us to describe general laws that can be applied to everything we can perceive. Extending Darwin’s theory [21], the present framework can be used to reframe “universal Darwinism” [22], introducing the laws that describe the general behaviour of information as it evolves. These laws are only *tentative*, in the sense that they are only presented with arguments in favour of them, but they still need to be thoroughly tested.

4.1 Law of Information Transformation

Since information is relative to the agents perceiving it, *information will potentially be transformed as different agents perceive it*. This is a generalization of the Darwinian principle of random variation, and ensures *novelty* of information in the world. Even when there might be static information,

¹ Shannon’s information [17] deals only with the technical aspect of the transmission of information and not with its *meaning*, i.e. it neglects the semantic aspect of communication.

different agents can perceive it differently, potentially transforming it. Another way of pronouncing this law is by stating that information *interacting* with information can potentially transform information. Through evolution, the transformation of information generates a *variety* or *diversity* that can be used by agents for novel purposes.

For example, RNA polymerase (RNAP) can make errors while copying DNA onto RNA strands. This slight random variation can lead to changes in the proteins for which the RNA strands serve as templates. *Some* of these changes will lead to novel proteins that might improve or worsen the function of the original proteins.

4.2 Law of Information Propagation

Information tries to propagate as fast as possible. Certainly, only some information manages to propagate. In other words, we can assume that different information has different “ability” to propagate, also depending on its environment. The “fitter” information, i.e. that which manages to persist and propagate faster and more effectively, will prevail over other information. This generalizes the Darwinian principle of natural selection, the maximum entropy production principle [23] (entropy is also information), and Kauffman’s tentative fourth law of thermodynamics².

In relation with the law of information transformation, as information requires agents to perceive it, information will be potentially transformed. This source of novelty will allow for the “blind” exploration of better ways of propagating information, according to the agents perceiving it and their environments.

Extending the previous example, if errors in transcription made by RNAP are beneficial for its propagation (which entails the propagation of the cell producing RNAP), cells with such novel proteins will have better chances of survival than their “cousins” without transcription errors.

4.3 Law of Requisite Complexity

Taking into account the law of information transformation, transformed information can increase, decrease, or maintain its previous complexity. However, *more complex information will require more complex agents to perceive it.* This generalizes the cybernetic law of requisite variety [2].

The so called “arrow of complexity” in evolution [20] can be explained with this law. If we start with simple information, its transformation will produce by simple drift [24] increases in the complexity of information, without any goal or purpose. This occurs simply because there is an open niche for information to become more complex as it varies. But this also promotes agents to become more complex to exploit novel (complex) information and propagate it. Evolution does not need to favour complexity in any way: information just propagates to every possible niche as fast as possible, and it seems that there is often an “adjacent possible” [6] niche of greater complexity.

For example, it can be said that a protein (as an agent) perceives some information via its binding sites, as it recognizes molecules that “fit” a site. More complex molecules will certainly need more complex binding sites to be perceived by a protein. Whether complex molecules are better or worse is a different matter: some will be better, some will be worse. But for those which are better, the complexity of the proteins must match the complexity of the molecules perceived. Following the law of information transformation, there will be a variety of complexities of information. The law

² “The workspace of the biosphere expands, on average, as fast as it can in this coconstructing biosphere” [6, p. 209]

of requisite complexity just states that the increase in complexity of information is determined by the ability of agents to perceive more complex information.

Since more complex information will be able to produce more variety, the *speed* of the complexity increase will escalate together with the complexity of the information.

4.4 Law of Information Criticality

Transforming and propagating information will tend to a critical balance between its stability and its variability. Propagating information will try to maintain itself as much as possible, but transforming information will try to vary as much as possible. This struggle leads to a critical balance analogous to the “edge of chaos” [25,26], self-organized criticality [27,28], and the “complexity from noise” principle [29].

This law can generalize Kauffman’s four candidate laws for the coconstruction of a biosphere [6, Ch. 8]. Their relationship with this framework demands further discussion, which is out of the scope of this paper.

A well known example can be seen with cellular automata [25] and random Boolean networks [26,30]: stable (ordered) dynamics limit considerably or do not allow change of states, while variable (chaotic) dynamics change the states too much, losing information. Following the law of information propagation, information will tend to a critical state between stability and variability to maximize its propagation: if it is too stable, it will not propagate, and if it is too variable, it will be transformed. In other words, “critical” information will be able to propagate better than stable or variable one, i.e. as fast as possible.

4.5 Law of Information Organization

Information produces constraints that regulate information production. These constraints can be seen as *organization* [6]. In other words, evolving information will organize itself (by transformation and propagation) to regulate information production. According to the law of information criticality, this organization will lie at a critical area between stability and variability. And following the law of information propagation, the organization of information will enable it to propagate as fast as possible.

This law can also be seen as information having a certain control over its environment, since the organization of information will help it withstand perturbations. It has been shown [31,32,33] that using this idea as a fitness function can lead to the evolution of robust and adaptive agents, namely maximizing the mutual information between sensors and environment.

A clear example of information producing its own organization can be seen with living systems, which are discussed in the next section.

5 On the Notion of Life

There is no agreed notion of life, which reflects the difficulty of defining the concept. Still, many researchers have put forward properties that characterize important aspects of life. *Autopoiesis* is perhaps the most salient one, which notes that living systems are self-producing [34,35]. Still, it has been argued that autopoiesis is a necessary but not sufficient property for life [36]. The relevance of autonomy [37,38,39] and individuality [40,39] for life have also been highlighted .

These approaches are not unproblematic, since no living system is completely autonomous. This follows from the fact that all living systems are open. For example, we have some degree of autonomy, but we are still dependent on food, water, oxygen, sunlight, bacteria living in our gut, etc. This does not mean that we should abandon the notion of autonomy in life. However, we need to abandon the sharp distinction between life and non-life [20,39], as different degrees of autonomy escalate *gradually*, from the systems we considered as non-living to the ones we consider as living. In other words, life needs to be a fuzzy concept.

Under the present framework, living and non-living systems are information. Thus, the following notion of life can be given:

Notion 3. *Living information is that which produces its own information.*

Being more specific—since all systems also receive information—a living system produces more (first order) information about itself than the one it receives from its environment. Following the law of information organization, this also implies that living information produces its own constraints (organization) to regulate itself. All information will have constraints from other (environmental) information, but we can measure (as second-order information) the proportion of internal over external constraints to obtain a “degree of life”. If this is greater than one, then the information regulates by itself more than the proportion that is regulated by external information. In the opposite case, the degree of life would be lesser than one.

Certainly, some artificial systems would be considered as living under this notion. However, we can make a distinction between living systems embodied in or composed by biological cells [41], i.e. life as we know it, and the rest, i.e. life as it could be. The latter ones are precisely those explored by artificial life.

6 On the Notion of Cognition

Cognition is certainly related with life [42]. The term has taken different meanings in different contexts, but all of them can be generalized into a common notion [11]. Cognition comes from the Latin *cognoscere*, which means “get to know”. Like this,

Notion 4. *A system is cognitive if it knows something [11, p.135].*

From Notion 2, all agents are cognitive, since they *know* how to act on their environment. Thus, there is no boundary between non-cognitive and cognitive systems. Throughout evolution, however, there has been a *gradual* increase in the complexity of cognition [11]. This is because all agents can be described as possessing some form of cognition, i.e. “knowledge” about the (first-order) information they perceive.

Certainly, there are different types of cognition³. We can say that a rock “knows” about gravity because it perceives its information, which has an effect on it, but it cannot *react* to this information. Throughout evolution, information capable of maintaining its integrity has prevailed over that which was not. *Robust* information is that which can resist perturbations to maintain its integrity. The ability to react to face perturbations to maintain information makes information *adaptive*, increasing its probability of maintenance. When this reaction is made before it occurs, the information is *anticipative*⁴. As information becomes more complex (even if only by information transformation),

³ For example, human, animal, plant, bacterial, immune, biological, adaptive, systemic, and artificial [11].

⁴ For a more detailed treatment on robustness, adaptation, and anticipation, see [16]

the mechanisms for maintaining this information also become more complex, as stated by the law of requisite complexity. This has led gradually to the advanced cognition that animals and machines possess.

7 Future Work

The ideas presented here still need to prove their usefulness. One way of doing this would be with a simulation-based method. Being inspired by ϵ -machines [43,44], one could start with “simple” agents that are able to perceive and produce information, but cannot control their own production. These would be let to evolve, measuring if complexity increases as they evolve. The hypothesis is that complexity would increase (under which conditions still remains to be seen), to a point where “ ϵ -agents” will be able to produce themselves depending more on their own information than that of the environment. This would be similar to the evolution in Tierra [45] or Avida [46] systems, only that self-replication would not be inbuilt. The tentative laws of information presented in Section 4 would be better defined after such a system would be studied.

One important aspect that remains to be studied is the representation of thermodynamics in terms of information. This is because the ability to perform thermodynamic work is a characteristic property of biological systems [6]. This work can be used to generate the organization necessary to sustain life (cf. law of information organization). It is difficult to describe life in terms of thermodynamics, since it entails new characteristic properties not present in thermodynamic systems. But if we see the latter ones as information, it will be easier to describe how life—also described as information—evolves from them.

A potential application of this framework would be in economy, considering capital, goods, and resources as information (a non-conserved quantity) [47]. A similar benefit (of non-conservation) could be given in game theory: if the payoff of games is given in terms of information (not necessarily conserved), non-zero sum games could be easier to grasp than if the payoff is given in material (conserved) goods.

8 Conclusions

This philosophical paper introduced ideas that require further development and extension. Still, a first step is always necessary, and hopefully feedback from the community will guide the following steps of this line of research. Here mainly philosophical issues were addressed. The explanatory and predictive benefits of this framework still remain to be addressed.

Different metaphors for describing the world can be seen as different languages: they can refer to the same objects without changing them. And each can be more suitable for a particular context. For example, English has several advantages for fast learning, German for philosophy, Spanish for narrative, and Russian for poetry. In other words, there is no “best” language outside a particular context. In a similar way, I am not suggesting that describing the world as information is more suitable than physics to describe physical phenomena, or chemistry to describe chemical phenomena. It would be redundant to describe particles as information if we are studying only particles. The suggested approach is meant only for the cases when the material approach is not sufficient, constituting an alternative worth exploring to describe evolution.

It seems easier to describe matter and energy in terms of information than vice versa. Moreover, information could be used as a common language across scientific disciplines [48].

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