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Reductionist perspectives and the notion of information

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Abstract

Reductionism is the dominant stance of biology. According to this perspective, biological phenomena have to fit with physical explanations. Some biologists thought that the introduction of the idea of program was a sound way to overcome both physicalism and reductionism. We argue instead that the introduction of information theory into biology did not liberate biology from reductionism. We argue that the adoption of information in biology is an erroneous transposition from a specific mathematical domain to one where it does not belong. Indeed, the mathematical framework of the information theory is too rigid and discrete to fit with biological phenomena. Therefore, information in biology represents an inappropriate metaphor. Then, we make explicit the use of metaphors and the choice of explanation mode. We argue that the choice of explanation is not neutral. Furthermore, the use of metaphors in science becomes dangerous when they take the place of theories and they lose their paradoxical content.

Keywords: information, metaphor, reduction, entropy, complexity, mathematical invariance

> To think that the genome completely determines the organism is almost as absurd as thinking that the pipes in a large cathedral organ determine what the organist plays.
>
> D. A. Noble "Theory of biological relativity", Interface Focus. 2012

1. Introduction

For at least two centuries two distinct and even antagonistic stances co-existed in biology. In current terminology, we refer to them as reductionism and organicism. The former is going to be addressed in this article while the latter is addressed in Mossio et al (this issue). The history of physics shows that a new phenomenon has always engendered new observables and principles. For instance, Galileo proposed momentum and its principle of conservation (inertia); thermodynamics studies trajectories in a relevant phase space: pressure, volume, temperature. A new observable, entropy, has greatly enriched physics by providing a principle that can be applied to any form of energy transformation: the second principle of thermodynamics[1]. Does biology operate similarly regarding the choice its observables and invariants? At the beginning of the 20th century, the central goal was to find observables and principles to understand the phenomenon of reproduction resulting in the hereditary transmission of phenotypes. In this context, the search for a proper observable specific to biology headed toward the notions of encoding and of program that are at the core of the theories of information.

In this paper, we argue that information is problematic for biology for at least three of the reasons that we will analyze here. First of all, we claim that the transposition of the mathematical theory of information into the biological field is scientifically erroneous. To this aim, in the first section, we analyze the incompatibility between the information sciences and the biological object.

The second reason is related to a general problem of reductionism. According to the distinguished biologist Ernst Mayr, the information field provides an anti-reductionist framework for biology. Despite this viewpoint, we argue that applying the theory of information to biology belongs to a reductionist attitude. In the second section, we analyze this reductionist approach, and we point out the relationship with determinism. We show that the reductionist stance hides the general idea according to which classical determinism is the regular form of scientific knowledge and that this is also true when information theory is applied to biology. For the reasons analyzed in the first section, it will be clear that the deterministic theoretical framework is inappropriate for biological theorizing.

Faced with this kind of criticism, oftentimes biologists defend the use of the idea of information, as well as the concepts of signal and program, as *just* useful metaphors

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[1] See Soto & Longo (this issue), see also Bailly and Longo, 2011; Chibbaro et al., 2015.

or fruitful ways with which to approach a phenomenon by using an image borrowed from common sense. That is why, in the last and conclusive section, we analyze the general use of metaphors and common sense in science, and we show their dangerous consequences. This is particularly the case of the idea of information and the genetic program in biology because, as we will explain, here we face a dead metaphor.

2. Information Sciences and Biology

The use of the concept of information in biology appeared in the middle of the 20th century, but it is related to what happened at the beginning of that century when the possibility of isolating chromosomes was coupled with the new concept of the mendelian gene as a functional unit of recombination. Mendel's writings did not directly imply this concept, which appeared after 1900 when Hugo de Vries, Erich von Taschermark, and Carl Correns "rediscovered" Mendel (see Pichot, 1999). Johannsen (1911), then, replaced the term *mendelian factor* with the term *gene* and suggested the consequent distinction between genotype and phenotype (see Moss, 2004). Therefore, the idea of associating a phenotype with a segment of these chromosomes appeared. Schrödinger (1944) then, realized that this association was not well founded in a law: "It seems neither adequate nor possible to dissect into discrete 'properties' the pattern of an organism which is essentially a unity, a 'whole'. Now, [...] a pair of ancestors are different in a certain well-defined respect [...] we locate in the chromosome the seat of this difference. Difference of properties, to my view, is really the fundamental concept rather than the property itself" (Schrödinger, 1944, p. 10). This great physicist understood that differential analysis does not allow for the deduction of a *law* in the physical sense. In order to obtain a law in the proper sense, it would be necessary to propose a direct causal link, between the *wild gene* and the normal phenotype. He introduced the notion of encoding, borrowed from the new sciences of coding, in order to provide a theoretical framework and establish this hypothetical correlation. In other words, the fact that a mutation modifies the structure of an enzyme does not allow for the deduction of a direct *one gene - one enzyme* correlation[2] (following Beadle & Tatum, 1941). The notion of information was introduced as a theoretical framework providing this direct causal link. However, it is scientifically inexcusable to adopt this notion in biology without clarifying its usage with respect to at least two of the fields which make rigorous use of it. These fields are information elaboration (Turing-Kolmogorov), (Turing, 1936) or algorithmic theory of information (see Calude, 1994; Davis, 1958), and information transmission (Shannon-Brillouin), (Brillouin, 1962, Shannon 1948).

The Central Dogma of molecular biology (Crick & Watson, 1953; Crick, 1970) suggested that the description of the chemical structure of the DNA molecule represents well the core of the informational/algorithmic view of biological phenomena. The idea here is that the expression from nucleic acid to protein is a unidirectional flow of information. Which information theory is involved here? Despite the different scientific implications of these theories, there is a significant confusion in biology which is rarely clarified. Maynard Smith (2000) explicitly refers to information elaboration (Turing-Kolmogorov) and to information transmission (Shannon-Brillouin) while emphasizing the relevance of the *latter* in biology. However, in the same text, he explains how molecular encoding can work as a short "recipe" (his wording) for generating complex, but organized (ordered) objects. The analogy is then the recipe for describing a circle by the three parameters which determine it. This recipe is less complex and contains less information than a point by point description of the circle. On the contrary, a totally disordered set can only be described point by point, as it does not obey as a rule. Now, this notion of a short (compressed) program for an organized object and of (maximal) informational complexity of disorder is that of Kolmogorov, and it is *covariant* ("it grows together") with entropy (total disorder has maximal entropy). Note instead that, according to Shannon and Brillouin, complexity, as covariant with the quantity of information, is *contra-variant* with entropy and is in fact negentropy (it has the opposite sign and, thus, information decreases when entropy increases). This is also how physicists describe it, for sound reasons internal to the theory of "transmission of information" which thus differs greatly from Kolmogorov's one, a theory of "elaboration of information" (Longo, Miquel, Sonnenschein, & Soto, 2012).

Another important difficulty lies in the fact that information in the two senses explored above deals with the realm of the discrete. Now, in this discrete framework, that is a precise concept in mathematics, only the dynamics of the discrete parts are relevant for the explanation of the entire system. In biology these discrete parts are molecules, so molecules alone forcibly and fully retain the researchers' attention. In this context it would be very hard to integrate, as a *positive* contribution to the expression of information, others events such as torsion, pressure (see for example (Lesne & Victor, 2006; Farge 2003), the dynamics of contact, geometries and relative distances, which all causally contribute to gene expression. A computer (Turing) or a cable (Shannon) does not receive a positive contribution from these observables which are better understood using continuous mathematics. In fact, in both the mathematicalabove theories of information, grounded on the treatment of discrete sequences of signs, such material dynamics can only cause an increase in noise[3]. On the

[2] Which we now know to be an erroneous bijective correspondence.

[3] It would be possible and interesting to provide a theory of bio-information by integrating the theory of continua. Control theory,

contrary, in biology we need a theory that includes such dynamics in a causal sense because they have a specific role in the gene expression and in the morphological constitution of the organism. In short, biological processes, which take place in an organism simultaneously, are coupled to continuous dynamics that unfold in physical space and time.

Furthermore, in both theories of information, the flow of information does not depend on the material that carries the information. Crick refers to the Morse code when addressing genetic information. Now, the nice idea behind this practice of Morse-type encoding is that it depends neither on its form nor on the material which conveys it. It is possible to transmit Morse code through smoke clouds, light flashes, electric impulses, and so on. It is then possible to encode the signals using different pitches, different materials, colors, etc. This independence of the encoding from its material embodiment is actually at the core of the two great theories of information of the 20th century that we mentioned. In other words, information is an invariant with respect to the transformations pertaining to the physical medium or to the form of encoding. In fact, these transformations of material, leaving the informational content invariant, can be performed on the most complex of our informational machines, the computer. Specifically, if your machine is dying, due to the age of the material, you can transfer, via cable or wifi, the operating system, the compilers, all programs, onto another machine[4]. This radical *software vs. hardware* dualism of the Turing Machine is at the core of all contemporary computer science. With their differences, as discussed above, these two theories share the same radical properties of well-theorized invariance, giving rise to central theorems for both theories.

What about biology? At which level would it be possible to find the fundamental invariant of information? Do we have another way to encode such "genetic information" than through the DNA and RNA? Are there other forms of transmission and elaboration of this "information", otherwise than the *specific* molecular cascades active within the cell? Is it possible to encode the informational "content" of these molecules, carried in DNA, by using different materials, such as wood, metal, or a different chemistry, or beeps, flashes, octets, pairs of colors? Would this transposition alone be able to generate living organisms? Evidently not: there only exists the physico-chemical materiality of DNA and RNA with their very specific roles in biological phenomena. Biological dynamics radically depend on their materiality, and this is far from the independence of matter proper to digital information theories. Moreover, DNA or RNA are not "rigid" and this is essential to biological processes: for instance, redundancy or, better yet, Edelman's degeneracy is omnipresent (Edelman, Gally, 2001). In short, it is not even possible here to speak of physical invariance/stability: the physical chemistries of DNA and RNA do not allow themselves to be set once and for ever. By definition they change while being conserved.

Rather, as proposed in Mossio et al. (this issue), the proper biological observable is "material organization". From the structure of DNA to neuronal dynamics, biological activities exist solely in their highly organized physical, chemical and biological materiality. Quite the opposite of information, the polyvalent use of a given material is a core property in biology. Would it be possible to relate information to 'processes' instead of 'materials' (molecules)? Would this save the notion of information for biology? We reject this option. Biological processes, as shown in chapter 4, are subordinated to their material realization and to the organization of the living. They can not be considered independent from them nor as "informational invariants", in the scientific sense of this term.

In conclusion, there is no reason for the physico-chemical trace of a history, such as DNA, to be considered as "information". A rock shaped by its history of rolling along the current of a stream does not transfer information by hitting, deforming, or breaking other rocks. Information is in the mind of the geologist who studies its origin, not in the rock itself nor in its dynamics, which, if we choose to use such a word, may transmit a form or chemical structures.

3. Reductionism, determinism and mechanistic explanations in biology

Ernst Mayr (1961) thought that applying to biology the notion of a genetic program, borrowed from information theories, was a good way to provide an autonomous description of biology with respect to physics. The genetic program was, in his mind, an anti-reductionist approach. Here we show that, on the contrary, applying information theory to biology belongs to a form of reductionism and the theoretical consequences enhance our position according to which information is not an appropriate notion for biology.

Reductionism is a philosophical attitude commonly distinguished into three main types: ontological, methodological and epistemic reductionism (See Brigandt & Love, 2014). Ontological reductionism, called physicalism, is a general statement according to which there are no such things *separated* from physical (chemical) things, so that nothing but molecules constitutes an organism. Ontological reduction does not necessarily mean that the explanation of the physical level provides a complete explanation of the entire organism. It is more a form of *antisupernaturalism* that refuses any supernatural causes in biology such as intelligent design or vital forces. Methodological reductionism claims that the best way to explain a complex sys-

for instance, deals with information by differential equations in a continuum, not to mention the new productive area of Information Geometry (Barbaresco, Djafari, 2015), entirely ignored in (molecular) biology.

[4] In Manchester, during the 100th anniversary of Turing's birth (2012), students built a Turing machine made of Lego blocks ... and it works, it is Turing complete (albeit somewhat slow).

tem, such as an organism, is to access its lowest possible level; that is the molecular and biochemical one. Finally, epistemic reductionism is the idea that the knowledge of one scientific domain can be reduced to what is supposed to be a more fundamental body of scientific knowledge. This attitude claims the possibility of *translating* a group of scientific theories into another that is intended to be the primary. These three philosophical postures share the idea that physics is the fundamental level of a scientific representation of nature. In all the three cases the reduction goes from biology to physics. In other words, physics *is* nature and biology has to be, to different extents, subordinated to physics.

Classical geneticists, as well as early molecular biologists, were strongly committed to the idea that the living can be entirely explained by its physical and chemical dynamics. Here the three philosophical attitudes of reductionism, ontological, methodological and epistemological, converge. In fact, the physical and chemical dynamics are supposed to be the ontological composition of the living as well as the proper epistemic level of description and also the only way to understand the complexity of the living. This can be partially understood through a historical event. During the 19th century, there was a debate between biologists of two different schools of thought: the vitalists and the mechanists. Mechanicism focused on the research of objectivity for biology in order to provide a scientific foundation for this discipline otherwise vulnerable to metaphysical implications[5]. This need pushed numerous biologists to look at physics as a proper scientific model of description and analysis. In this context, a very peculiar form of reductionism surfaced in biological research. This reductionism groups the idea that the elementary components can explain the complex with the idea that biology has to be reduced into the language and the laws of chemistry and physics (See Rosenberg, 1985). Francis Crick, for instance, thought that explaining the living by its elementary dynamics corresponds to the conviction that biology is subordinated to physics (See Feltz, 1995). In this context, the Central Dogma is not only reductionist but strongly deterministic. The unidirectional flow of information from genes to protein, coupled with the strong specificity of the "one gene one enzyme" statement (Beadle & Tatum, 1941), belong to a view of the organism as a highly predetermined and predictable system. Of course, from time to time, some "noise", as said explicitly in (Monod, 1970), may add some randomness to the determination of the dynamics. Indeed, the level of reduction is not physics in general, but classical mechanics, a deterministic field. The theoretical framework that served as a model to biologists at this time was the strongly deterministic one of classical mechanics (the cell is a "Cartesian mechanism" for (Monod, 1970)). Here reductionism and determinism overlap and converge in a strong commitment: nature intrinsically corresponds to a necessary order; this order can be expressed by mechanistic causes that represent the universal law of the phenomenon. Through these laws, phenomena must be predicted. The relationship between reductionism, mechanistic explanation and determinism in biology is the consequence of transferring the theoretical framework of classical mechanics to biology. These three aspects are strongly related and it is hard to distinguish one from the other in the context of classical molecular biology. Ernst Mayr's thought is emblematic of this conceptual relationship, enriched by his attempt to stress the singularity of biology. According to Mayr, as mentioned above, the notion of a genetic program is the best way to establish the epistemological autonomy of biology with respect to physics (Mayr, 1961). The genetic program is inspired by the theory of elaboration information, which is a mathematical, not a physical theory. From Mayr's perspective, this would represent a methodological anti-reductionism because the physical level would not be directly involved in the description of the living. This paradigm, though, uses the same deterministic structure as that of classical mechanics: when the "causal relations" are analyzed in informational cascades, they follow exactly the early deterministic paradigms, in both Turing's and Shannon's approaches. That is, the transfer of this paradigm preserves many of the reductionist and physicalist consequences related to this classical reference to physics, starting from the Laplacian characteristic of the system itself. That means that the organism is a deterministic system in which it is in principle possible to predict the future dynamics (it is "Laplacian"), both in ontogenesis and in phylogenesis, by knowing the present state of the "determining" elements of the system: DNA sequences and genes. The rest provides at most "conditions of possibilities" and noise, as rigourously spelled out in (Mondo, 1970). This is more generally true in the neo-darwinian approach, as strongly represented by Mayr. In fact, according to neo-darwinism, natural selection applies exclusively to the DNA level that has to preserve a deterministic structure. Even if natural selection can not be reduced to a Laplacian mechanistic process that includes all the ancestors of the organism and their environments, the level where natural selection applies is deterministic. Otherwise said, the fact that randomness is considered does not allow to depart from Laplacian determinism. After all, Laplace wass aware that randomness exist, that is why he studied probability. But in his theoretical framework, randomness appears as an external perturbation of deterministic dynamics (necessity) and it opposes to determination: it is "noise" (Monod, 1970). In the neo-darwinian frame, determinism is necessary for natural selection to apply. That is, Evolution preserves the deterministic molecular processes and is "the result of noise" plus selection (Monod, 1970).

The deterministic (Laplacian) nature of the coding and decoding processes was perfectly clear to Schroedinger, when he first proposed the notion of encoding for biology : "In calling the structure of the chromosome fibers a

[5] Vitalism was considered too close to finalism. See (Canguilhem 1968).

code-script we mean that the all-penetrating mind, once conceived by Laplace, to which every causal connection lay immediately open, could tell from their structure whether the egg would develop, under suitable conditions, into a black cock or into a speckled hen, into a fly or a maize plant, a rhododendron, a beetle, a mouse or a woman." (Schrödinger, 1944, 7)[6].

In conclusion, applying information theory to biology is not free from the attitude that tries to reduce complex biological systems to deterministic systems. On the contrary, it is grounded in this attitude and is responsible for imposing a too strong deterministic account for the living. As Turing observed in 1950, his Logical Computing Machine is "Laplacian ... as prediction is always possible". Similarly, in a Shannonian frame, the deterministic transmission of coded information must be predictable, modulo some noise. Thus, the informational reductionism brought us back not only to physics, but to a theory of determination that opposes determination to noise and that is largely superseded, even in classical physics, by the modern theory of dynamical systems, since Poincaré (1892). This theory integrates randomness as part of physical determination and understands it as unpredictability of (non-linear) deterministic dynamics, by a fine analysis of the interplay between measurement and non-linearity, see (Calude, Longo, 2015) for a synthetic frame for randomness in natural sciences.

4. Conclusion: Metaphors and common sense in science

Some metaphors are useful in science; they can guide and inspire scientific research in a deep way. In physics, for example, the Galilean metaphor of « the world as a book written in mathematical language by God » (See Galilei, 1957) is a very inspired metaphysical metaphor that guided the scientific revolution. It never became a way of explanation. That means that the Galilean scientific framework never appeals to entities like God or books in its formal conditions. It is *just a metaphor*, in the real sense of an abstract idea that inspires the gesture and the curiosity of the scientific attitude – even by a somewhat absurd or paradoxical reference (indeed, the universe does not have the structure of a book). However, metaphors become dangerous when they take the place of theories, and they lose their paradoxical content. Fresh metaphors in science are metaphors that have not been reduced to the common sense and reveal a new way of seeing. On the contrary, dead metaphors are metaphors that have lost their paradoxical references, and they literally take the place of the formal conditions of a theoretical framework. In this case, they become dangerous for the sciences because they crystallize a conservative thought into the common sense. This is the case for the metaphor of the genetic program related to information. This metaphor does not inspire research but replaces the theoretical framework in order to support the entire differential method and the reductionist attitude (see Davies, 2009; Longo & Tendero, 2007). In other words, the strong causal correspondence between genotype and phenotype is not proved by the differential method as we have shown above. On the contrary, by the reference to programmed informational dynamics, a Laplacian determination is supposed in order to maintain the general idea of this strong and unidirectional correlation, as in the common interpretation of Crick's Central Dogma. It is amazing to observe, as we did, that the founder of the "coding paradigm", Schrödinger, was perfectly aware of this, since 1944. Later, the metaphor in question became a theory because the theoretical framework appeals to entities related to this metaphor in order to justify and build itself: in the DNA there must be a true program, otherwise the strong correlation fails. This is also a problem related to the use of common sense in science. According to the French philosopher Gaston Bachelard, the uncritical acceptance of common sense is a serious issue for science. This is because, in general, common sense hides an entire *package* of metaphysical assumptions.

The general usage of determinism and predictability in biology is a clear example of this problem. Indeed, as we mentioned, even when methodological reductionism was questioned, as it was the case for Mayr, determinism remains the general model of scientific knowledge and inspires the metaphor of the genetic program. As a matter of fact, any programmable process is deterministic and predictable: it is Laplacian, as we know since Turing. Thus, the metaphysical *package* of classical determinism, namely the idea of a highly predetermined and predictable system built on the dynamics of the discrete and elementary parts, was transferred entirely to biological research. The scientific practice then tried to justify and confirm this general idea by data, starting by the search for steroespecific macromolecular interactions (they are required to transmit and elaborate information) and complete autoregulation of genes by genes. As Gaston Bachelard said very well: *There comes a time when the mind's preference is for what confirms its knowledge rather than what contradicts it, for answers rather than questions. The conservative instinct then dominates and intellectual growth stops.* (Bachelard, 2002, p. 25)

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[6]Turing (1950) also explicitly acknowledges that his Machine, the founding mathematical structure for programming, is "Laplacian".

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