Bioinformation as a triadic relation

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Introduction

Rather than a unitary concept, *information* is seen today as a family of concepts with no clear interconnection, while the relationships of the members of this family with neighbouring notions —like knowledge, form, entropy, correlation, probability, meaning, order, organization, and complexity—also require clarification. Furthermore, measurements of information are normally interpreted as gauges of structural complexity, correlation, thermodynamic order, or potential information and as such are unable to discriminate biological functionality. The clarification of the concept of information and its relationships with other surrounding notions, along with the development of a measure of functional information, are, therefore, important tasks for philosophers of biology, especially since formulating biological theories in informational terms has become increasingly common. I hope that the following discussion will help fulfil these objectives.

In this paper, I first show how the concept of information gradually became a key notion in the biological sciences, and I describe some of the controversies that resulted from this development. Then, I go on to defend a concept of information as a triadic relationship. This concept contributes to producing a general measure of information, as well as aids in integrating the measure and specific uses of the concept of information into a single framework. Next, I present a general measure of information according to this concept. Finally, I revisit the role of information in biology and try to apply this concept of information to the case of biology. The upshot of this presentation is to clarify the relationships between information and surrounding concepts important for biology, and to form a sound approach to certain biological questions concerning bioinformation itself, such as the problem of its location.

Biology and the rise of information

The term *information* derives from the Latin *informatio*, meaning "explanation," "idea," or "representation." The verb *informo* can mean "to give form or shape," "to sketch," "to draw," "to instruct," "to represent," or "to form an idea" of something. In ancient times the term was used in both everyday and learned discourse, appearing, for example, in the works of Virgil, Cicero, Tertullian, and Augustine of Hippo (see Capurro, 1978). It was used in different contexts, including ontological ("to shape something"), epistemological ("to become acquainted through the sensorial or intellectual reception of a form"), pedagogical, and moral ("to instruct") ones, but was not the object of special philosophical reflection.

During the Middle Ages, the verb *informo* and its derivatives were incorporated into philosophical language from scholastic discourse. It is frequent, for example, in Thomas Aquinas (1225-1274 CE). Throughout this period, the verb retained its ontological, epistemological, didactic, and moral aspects as well as its active sense, whereby *informatio* was an action rather than a thing, viz., that of shaping and its result. Before going on to the modern uses of the term "information," let me mention two cases of its application, which could even be seen as precedents of its use in genetics. First, Varro (116 -27 BCE) describes the development of a fetus as a process of information, whereby it is "shaped" or "informed" (*informatur*). Second, Thomas Aquinas distinguishes between the biological process that brings a new life into the world *per modum informationis* and a non-biological process which brings something to life *per modum creationis* (see Capurro & Hjørland, 2003).

When, around the 14th and 15th centuries, the use of "information" spread into European languages from French, "investigation," "education," and "intelligence" were added to its traditional connotations. Perhaps because of the rejection of scholastic terminology, from then on “information” ceased to be a philosophical term, and others such as “impression,” “idea,” and “representation” were preferred. Descartes, Locke, Hume, Berkeley, Bacon, Kant, and others did not think of their epistemologies in terms of information. And in the few places where we find a word that derives from the term “information”, it had lost its ontological meaning and had become mainly an epistemological term. Now, information is understood as an idea or a representation that enters the subject’s mind. Modern idea-ism is obviously related to this shift from the view of information as an action to an idea (see Musgrave, 1993).

The term’s growth in importance, to the point of acquiring a central place in contemporary culture, began in the 19th century. It was bound up with the development of communication technologies—especially the telegraph—and with the use given to it in military intelligence service (Adriaans, 2007). Thus, information acquired economic and political value. Since then, theories of communication have been developed that seek to facilitate the transmission of the greatest possible amount of this new commodity at the lowest possible cost, in the shortest possible time, and with the maximum security. Since the Second World War, these developments have accelerated, as have those concerning computation. The linking of these two technologies and their omnipresence has done the rest. The term "information" now occupies a central place in everyday speech and in almost all sciences and disciplines, from computer science, biology, and librarianship to journalism, sociology, and philosophy.

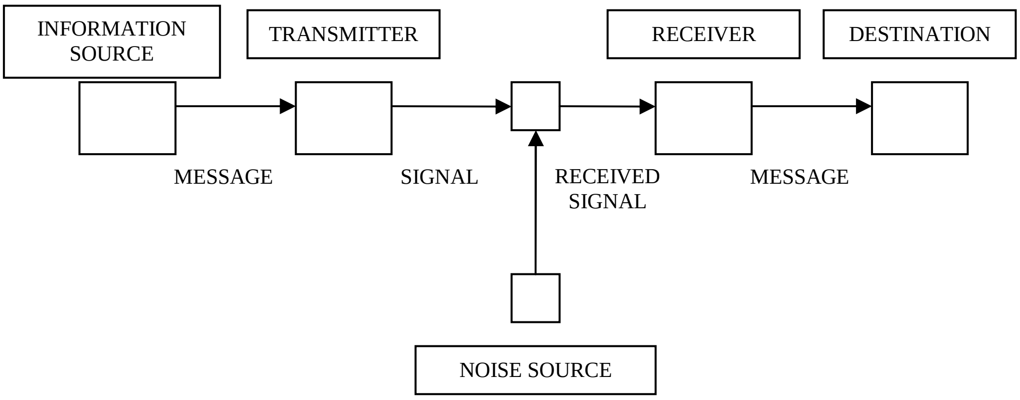
The study of reference for the theory of information is the classical book by Claude E. Shannon and Warren Weaver (1949). However, the term *information* does not even appear in its title, *The Mathematical Theory of Communication*. The expression *theory of information* comes probably from an article of Hartley (1928) entitled *Theory of Information Transmission*. Shannon focuses his attention mainly on the engineering problems of communication, but we should understand that his theory deals precisely with the communication *of information*. Weaver (Shannon & Weaver, 1949) offers some explanations regarding the very concept of information:

> Information must not be confused with meaning […] To be sure, this word information in communication theory relates not so much to what you *do* say, as to what you *could* say. That is, information is a measure of one's freedom of choice when one selects a message. If one is confronted with a very elementary situation where he has to choose one of two alternative messages, then it is

> arbitrarily said that the information, associated with this situation, is unity […] The amount of information is defined, in the simplest cases, to be measured with the logarithm of the number of available choices. (pp. 8-9)

Sahnnon identifies the elements that take part in the communication of information processes. He represents them by means of the following diagram (Shannon & Weaver, 1949, p. 34):

Figure 1:



The main objective of Shannon was to apply his theory to the technical systems of communication. This is the reason why his diagram includes a transmitter, which function consists in transforming the original message –for instance, a sequence of letters- into a signal suitable for transmission over the channel. The channel is thought by Shannon as a "pair of wires, a coaxial cable, a band of radio frequencies, a beam of light, etc" (p. 34). At the other part of the channel appears a receiver that performs the inverse operation of what is done by the transmitter. But, we could design even more detailed diagrams, with more *boxes*, according to the domain and to the degree of precision of the problems we are trying to apply the theory to (see, for instance, Escarpit, 1976; Gueroult, 1966; Moles, 1972). In Shannon's diagram, the function of codifying and decodifying the message are assumed by the transmitter and the receiver respectively, but we could envisage new *boxes* for an encoder and a decoder. Shannon himself introduced another diagram more complex, with a secondary feedback channel for data correction (Shannon & Weaver, 1949, p. 68).

In the opposite sense, we can trace more simple diagrams with no more than three elements: a source or emitter, a channel and a receiver (see Singh, 1966). We can even adopt a more abstract interpretation of Shannon's theory, a non-dimensional interpretation, free from space-temporal connotations. Abramson (1963) interprets a channel of information from a mathematical point of view as a simple relationship between the probabilities of two sets of symbols. An information channel is determined only by an incoming alphabet, an outgoing alphabet and a set of conditional probabilities. For instance, $P(b_j | a_i)$ is the probability of receiving the symbol b_j if a_i was emitted.

A source of information is no more than a set of symbols and their corresponding probabilities.

As Shannon himself warns (Shannon & Weaver, 1949, p. 31), his theory does not approach all the problems regarding information concept. In order to understand which types of problems are at stake here, the distinction established by Weaver (Shannon & Weaver, 1949) is still a very useful guide. He notes three types of problems concerning information:

(A) There are *technical problems* concerning the maximum amount of information that a message can convey. These concern the statistical regularities of the source like the internal structure and constraints of the messages, together with the conditions of noise and equivocation of the channel. Given these conditions, we ask, "What is the best possible configuration of the message?" Thus we have problems at a *syntactic* level, of the type dealt with by Claude Shannon's mathematical theory of communication. The measure of complexity proposed by Andrey Nikolaevich Kolmogorov is also at the syntactic level (Kolmogorov, 1965; Solomonoff, 2003; Li & Vitányi, 1997; Grünwald & Vitányi, 2003).

(B) There are *semantic problems* concerning the meaning and truth of the messages, and the correlation between the message and some other thing. Weaver makes it clear that Shannon's theory does not seek to explain problems at this level or at the next one. In the last few decades, several theories have appeared that do deal with semantic aspects of information (Barwise & Seligman, 1997).

(C) Finally, there are *pragmatic problems* concerning the efficiency of the message regarding the alteration of the receiver's behaviour. Weaver (Shannon & Weaver, 1949) says that "the *effectiveness problems* are concerned with the success with which the meaning conveyed to the receiver leads to the desired conduct on his part" (p. 5). In biological terms, we find here the functional aspects of information, its ability to affect the receiver's behaviour in a functional or adaptive sense.

Recently, Luciano Floridi (2007) distinguished among "information *as* reality," "information *about* reality," and "information *for* reality." It is tempting to correlate these categories with Weaver's levels. On the syntactic level, what we study is "information as reality," viz., the properties of the message itself. On the semantic level, we deal with "information about reality," or what a message tells us about another part of reality. On the pragmatic level, we observe the capacity of a message to alter reality. This is like saying that we observe the message as "information for (making or modifying) reality." A variety of approaches have arisen to address the levels of information. Floridi (2007) identifies as many as seven, but -as he notes- all of them are concerned with syntactic or semantic problems. However, since our interest in this discussion focuses on living systems, our concern is mainly with pragmatic or functional problems.

Since the 1950s, the notion of information—either as a metaphor, analogy, or real entity—has become increasingly important in most fields of biology (see Paton, 1992). It has even been used to define life (see Tipler, 1995, pp. 124-7). The biological sciences have adopted a theoretical perspective derived from information theory, together with developments in modern genetics and evolutionary science. This perspective holds that all biological processes involve the transfer of information, and has been called *bio-informational equivalence* (Stuart, 1985; see also Burian and Grene, 1992, p. 6).

A glance at the current bibliography (see Queiroz, Emmechec & El-Hani, 2007; Jablonka, 2002) will suffice to show that, since Stuart's paper, the use of the concept of information in biology has become more widespread (for a historical perspective see Kull, 1999; Collier, 2007). In molecular biology, biomolecules are considered to contain information and are the result of informational processes (Holzmüller, 1984). In genetics especially, biological thinking is shaped by the idea of information transfer (simply by way of example see Brandt, 2005; Kjosavik, forthcomming), while in development biology, much is said about the expression of information and phenotypic information (Waddington, 1968; Oyama, 2000). In cell biology (Albrecht-Buehler, 1990; Marijuan, 1989, 1991), tissue biology, zoology, and botany, we study different ways of communicating information with chemical, neuronal, or linguistic bases (Stegmann, 2005; Pfeifer, 2006). In ecology the concepts of complexity and biodiversity are closely bound up with information through notions of entropy and order (Margalef, 1968).

In neurophysiology, the study of communication, storage, and processing of information is central, as are the various electric and chemical codes (Baddeley, Hancock & Földiák (eds.), 2000). The immune system is also researched in terms of knowledge; both acquired and accumulated (Forrest & Hofmeyr, 2000). Evolution, from the origin of life on, is thought of as the accumulation of information in the macromolecules (Elsasser, 1975; Küppers, 1990; MacLaurin, 1998;

Moreno & Mirazo, 2002). The latest research into the human genome and the genomes of other organisms has required the application of powerful methods of computation, and this coming together of disciplines has given rise to what is known as *Bioinformatics* (see Nishikawa, 2002, and, in general, the journal *Bioinformatics)*.

The concept of information, however, is also central to epistemology and the cognitive sciences and, as several research programmes are attempting to link the cognitive phenomenon with its biological basis, , it would be desirable to have one general concept of information that could be applicable to both cognitive and biological contexts. We could remember, as classical examples of such programmes, the Evolutionary Epistemology along the lines of Lorentz and Wuketits (1983), or Popper (1990), the Piagetian Epistemology (Piaget, 1970), the Psychobiology (Bond & Siddle, 1989), the Evolutionary Psychology (Horan, 1992), the Cognitive Ethology (Allen, 1992), the Neural Darwinism (Edelman, 1987), and in general a widespread current tendency to naturalizing epistemology (see, for example, Giere, 1988). An analogy could be drawn among the programmes of artificial life, computational science, and the social sciences, where the confluence with biology is evident and the need for a common concept of information is urgent.

Despite its applicability to a broad range of disciplines, the informational perspective in biology is not without polemics, which in recent years have arisen over its need and usefulness. Some authors consider information a distinctively human phenomenon, so that its application in other fields is purely metaphorical. For others, the use of information concepts is redundant in fields like biology, which are subject to general laws of matter and energy. They think that biological phenomena should be explained in mechanical, electromagnetic, chemical and thermodynamic terms, thus rendering informational considerations superfluous. According to this last perspective, to speak of information in biology would just be an odd way of speaking of correlation and causation (see, for instance, Stuart, 1985; Griffiths, 2001; Sarkar, 1996, 2000; Janich, 1992; Kitcher, 2001).

Many researchers, however, think that the informational perspective sheds considerable light on biological phenomena, allowing us to understand them in a way otherwise impossible (Maynard Smith, 2000; Queiroz, Emmechec & El-Hani, 2007). Here, I do not seek to argue in favour of this position, which I consider more reasonable, for it is already defended elsewhere in this book (see also *Philosophy of Science* 67 (2); Maynard Smith, 2000a; Godfrey-Smith, 2000; Griffiths, 2001; Roederer, 2005; Avery, 2003; Yockey, 2005). Thus assuming the informational perspective to be useful in biology, I now propose to present the kernel of a theory (concept and measure) that should contribute to clarifying the biological applications of information.

Information as a triadic relationship

Some authors have viewed information as a thing, third substance, or primitive element. Wiener (1961) thinks that information "is information, not matter or energy" (p. 132). Also, information has been seen as a property of a thing in terms of form, order, organization, negative entropy (Brillouin, 1962), complexity (Kolmogorov, 1965), or diversity (Margalef, 1980). Information as a property raises the problem of its location, which is a recurrent difficulty and, as such, one of the major arguments against the bioinformational paradigm. Actually, the problem of information location would be unsolvable unless we abandon this view of information as a simple property. Third, we find information as a dyadic (semantic) and a triadic (pragmatic or functional) relation. As Barwise (1986) notes:

> But is information relational? Surely so. The basic intuition about the information content C_S of a situation s is that it is information *about* something besides s. [...] The account of the information content C_S of a situation s

> given by Dretske and that given by Perry and me differ on many points, but they do agree on the relational nature of information. (p. 326; see also Dennett 1987; Mackay, 1969; Küppers, 1990; Queiroz, Emmechec & El-Hani, 2007)

On the other hand, information as a thing or new basic substance should be the last hypothesis to explore, for the principle of ontological economy implies that, other things being equal, if some other hypothesis works, it is clearly preferable. The other three possibilities could be equated with the three parts of Weaver's classical distinction (1949). The *technical problems*, which Weaver places at the level A, are studied by considering the formal and statistical properties of messages. At this level we are dealing with information as a property. The semantic problems, or level B problems, are concerned with the dyadic relationship between the message and its meaning. The *effectiveness problems*, or problems of level C, imply three elements. Weaver (1949) suggests that they are the message, its meaning, and a change in the receiver's behaviour caused by the reception of the message (p. 5). Therefore, problems of level C have a pragmatic aspect, which in biological contexts could be construed as a function. For instance, the change in a cell behaviour caused by the reception of a genetic message may consist in the accomplishment of a given function such as the synthesis of a determined protein.

I shall argue that information should be conceived of as a relationship, specifically demonstrating the need for a *triadic* relationship. On my account, pragmatic or functional information are envisioned as the basic and more general concept of information, while the others could be derived by abstraction, ellipsis, or addition. Even Shannon (1949) implies the functional and relative aspects of information, stating that "the fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point" (p. 31). One must suppose that the mere material transfer of what has been produced would not be information, while reproduction itself is worthless unless it refers to what has been produced. The receiver of information can be so called only if it can relate what is received to what was emitted.

I draw inspiration also from Charles S. Peirce's ideas, but using neither his terminology nor his technical niceties. Nor, unlike Queiroz, Emmeche, and El-Hani, do I attempt a thorough application of his semiotics to the concept of information. On the other hand, I do share with these thinkers an essentially Peircean conception of information as a triadic relation.

Another point in favour of information as a triadic relation is that it enables us to defend a general measure of information as well as to integrate the different measures and notions of information. This pragmatic or functional concept of information is also the concept that best adapts to biological contexts, where functional explanations are very common. We consider satisfactory an explanation of an organ or a molecule only if it includes reference, not only to its structure and material composition, but also to its function in the organism. For Peirce (1931-35), precedents include:

> All dynamical action, or action of brute force, physical or psychical, either takes place between two subjects...or at any rate is a resultant of such actions between pairs. But by semiosis I mean, on the contrary, an action or influence which is or involves a cooperation of three subjects, such as a sign, its object and its interpretant, this three-relative influence not being in any way resolvable into actions between pairs. (vol. 5. p. 484)

From these precedents, let us now construe the triadic informational relation in a slight different terminology. Information therefore implies a relationship between *i*) a message, m, which may be any event, linguistic or otherwise; *ii*) a system of reference, S, which the message informs the receiver about, and *iii*) a receiver, R. The receiver is a formal scheme resident in a concrete subject (a human being, another living system, a part of a living system, an ecosystem, a cell, a computer, etc.). A concrete subject could, of course, use more than one receiver and use them alternately (playing with different "hypotheses") or successively (owing to an evolutionary or individual process of learning). Peirce could be quoted again as he clearly differentiates the interpreter (the concrete subject) from the interpretant (the abstract scheme connecting sign and object). We can also see the receiver as an internal (that is, resident in a concrete subject) predictive model of S, along the lines suggested by Rosen (1985), who characterizes living beings as "anticipatory systems."

Some elements entering into one informational relationship could participate in another by playing a different role: the element playing the role of receiver in an informational relation could be a message in another; for example, a scientific theory can be viewed as a receiver offering us expectations about some domain. At this level, empirical data are messages to the theory. But a scientist could opt for a certain theory, considering it better confirmed than others, in which case the theory becomes a message to a receiver (in the scientist) dealing with theoretical alternatives. A system of alternative messages in one relation can, in another, be a system of reference, and vice versa—and the process could be iterated *ad infinitum*. A segment of DNA can be a message informing the appropriate part of the cell about the mRNA to be synthesized. The same mRNA, hitherto part of a system of reference, may later become a message informing the cytoplasm about the synthesis of a certain protein, and so on. "Semiosis entails," as Queiroz, Emmeche and El-Hani (2007) state using Peircean vocabulary, "the installation of chains of triads" (p. 60). This is why a metaphor like "the flow of information" is sometimes useful.

Comparing this triadic scheme to the classical one (see above figure 1), it may seem surprising that the emitter or source is not even mentioned, but that is because it should be considered a system of reference when the information that R receives through a message is about the emitter itself. On the other hand, in determining intended meaning, the emitter acts as a virtual receiver, and could be mathematically construed as such. Likewise, Millikan (1989) states that we should "focus on representation *consumption*, rather than representation production. Devices that *use* representations determine them to be representations" (pp. 283-284). Furthermore, there is often no specific emitter in non-linguistic contexts, like some biological ones, so a general theory of information should not demand the presence of an emitter.

The case of channel is more complex because usually we have a dimensional image of it. However, it is possible to construe a channel in a more abstract way, as a set of conditional probabilities, along the lines suggested by Abramson (1963). In the same spirit Barwise and Seligman (1997) suggest that a channel could be understood basically as an objective correlation of any degree between two domains.

Also relevant is the fact that a message gives information on a system, that is, on its possible states, not only on one of them. “The concept of information”, as Weaver (Shannon & Weaver, 1949) states, “applies not to the individual messages […] but rather to the situation as a whole” (p. 9). If a message increases the estimated probability of a state in the system, that of the others obviously decreases. This is one of the reasons why I prefer to talk about a *system of reference* rather than an *object* as in Peircean terminology.

Most of the conceptual problems concerning information stem from ellipsis, even the opinion that there are many different unrelated concepts of information. We often speak about the information of a message with no reference to a receiver or a referential system, although both of them exist implicitly. Information is always, as it were, functional, transitive, and pragmatic. The message is always referred to something by a receiver; otherwise it is not a message, just an event (Millikan, 1989, p. 286). If messages were not referred to something by a receiver, Griffiths (2001) would be perfectly right to say that "most information talk in biology is a picturesque way to talk about correlation and causation" (p. 400).

However, factors conditioning information are often mistaken for information itself. Such is the case regarding the formal characteristics of the system of reference, and either those of the message or the system to which it belongs. The correlation between the messages and the system information is given about also affects the amount of information involved, but neither this correlation nor form constitutes the information itself. For instance, we could obtain information on the hour pointed by a clock by observing another one. This is possible when a close correlation exists between both of them. Nevertheless, correlation by itself does not equal information, but it is only a factor that conditions the amount of information.

In order to make clear my proposal, let us say that our rendering of the notion of information differs from the classical shannonian diagram, but it is, at the same time, clearly related with it. In the first place, I propose to begin from the level C, that of the pragmatic or functional problems. Then I shall try to give a reinterpretation of other theories dealing with problems on levels A and B as restricted or ideal pragmatic theories. If we agree with MacKay (1969) in that "Information is what information does" (p. 41; see also Benthem, 2007), then a general theory of information should start from the pragmatic level, and only then move on to a reconstruction of the rest. Second, I propose taking the receiver as pivotal point for information relation, following Millikan's advice (1989). As we will see later, from a mathematical point of view, the distributions of probabilities defining the receiver will be sufficient for the accomplishment of the functions traditionally assigned to the source and the channel. This possibility is already suggested by the abstract interpretation of Shannon's theory given by Abramson (1968).

The relationship between the three elements above mentioned (m, R, and S) is informative when it changes the receiver's knowledge of the system of reference. By *knowledge* I mean the distributions of probabilities of the possible states of the system of reference in the receiver. Knowledge, therefore, should be understood here along the lines suggested by Karl Popper (1990) in a very general way:

> Can only animals know? Why not plants? Obviously, in the biological and evolutionary sense in which I speak of

> knowledge, not only animals and men have expectations and therefore (unconcious) knowledge, but also plants; and, indeed, all organisms [...] Flowering plants know that warmer days are about to arrive [...] according to sensed changes in radiation. (pp. 9, 10, 35)

In a remarkably parallel way, Rosen (1985) states: "I cast about for possible biological instances of control of behavior through the utilization of predictive models. To my astonishment I found them everywhere [...] the tree possesses a model, which *anticipates* low temperature on the basis of shortening days" (p. 7). This understanding of "knowledge" does not necessarily imply consciousness, so the notion is applicable to human and non-human living systems, and even to a computer.

We can describe information (I) as a relationship between a message (m), a receiver (R), and a system of reference (S). To this relationship there belong the triad formed by a message, receiver, and system of reference where the message alters the receiver's previous knowledge of the system of reference (Dretske, 1981, 2007). Moreover, the more probable an alternative is to a receiver, the more information will be received when a message says that a different one has occurred, unless it is a simple contradiction. So, for example, the introduction of a certain genetic message into the cytoplasm increases the probability of the cell carrying out a certain function, for the probabilities of alternative behaviour decrease. Now we can say that the receiver knows—or knows better—how to do something.

I am aware that by linking information with knowledge I also introduce epistemological problems like that of truth. As Dretske (2007) says, "we must carefully distinguish meaning, something that need not be true, from information which must be true" (p. 2). How can the concept of truth be applied to the case of living systems or computers? I cannot go into such a complex problem here, so I shall just make a suggestion. Perhaps it would be correct in these cases to talk about a kind of *practical truth*, a concept derived from Aristotle (NE, IV, 2). My answer would follow Popperian lines: truth goes hand in hand with functionality; *misinformation* exists when the message contributes negatively to the survival or functionality of the system. In continuity with this idea, at the conscious level, we can say that only non-falsified theories prosper, expectations that are not gainsaid. This position allows us to retain a belief in the possibility of a unified concept of information.

The informational relation may be perfectly objective (see Barwise, 1986; Fodor, 1986; Denbigh, 1985). For example, it is quite objective that a genetic message informs cytoplasm about synthesizing proteins, or that a statement informs one about the weather. It is clear that, even if one’s expectations about the weather are subjective, and the probabilities of a cell behaving in different ways are objective, both are equally objective phenomena to an observer. The observer does not directly take into account the probabilities in one’s mind, but those that he reckons one holds, nor does he directly bear in mind the probabilities of a given cell behaviour, but those he calculates. This makes it easier to reconcile the concepts of information used in biology with those used in classically epistemological contexts.

This does not mean that the information has been in the world since the beginning, preceding any subject capable of using it, as Dretske (1981) says. Without cellular machinery there is no connection between DNA and protein, just as without a hearer there is no connection between statement and weather. As Moreno and Mirazo (2002) state, the genetic message is, in principle, “decoupled from the dynamical organization of the system” (p. 73).

Information can be measured from the magnitude of its effects, that is, by the changes to the receiver’s knowledge of the system of reference. This is a traditional and standard way of measuring different physical magnitudes. Measuring information requires—like measuring anything else—a subject to do it, and this subject acts according to theoretical grounds. To assess the quantity of information given by a genetic message to cytoplasm, we need extensive biochemical knowledge. Our results, however, could be wrong or right, and we must remain aware that any attribution of a receiver to a subject is hypothetical, having at best the conjectural truthfulness of a scientific theory, but this does not make the informational relation any less objective.

It should finally be remembered that in measuring information, our knowledge of a given reality (the informational relation measured) changes, so the measurement of information is also an information relation (capable of being measured), but this does not cause any confusion of the two informational relations, for it is a normal recursive phenomenon (Hofstadter, 1979).

Measuring information as a relation

Our ways of measuring information do not do justice to the concept of information as described in biological literature. For example, genetic variation is understood to increase the capacity for information, whereas selection determines which variations are really functionally informative (Collier, 1988, 2007; Mayr, 1982; Wicken, 1987; Queiroz, Emmeche & El-Hani, 2007). Conversely, the standard measures of information are normally interpreted as gauges of potential information, structural complexity, or thermodynamic order; they cannot discriminate biological functionality.

But the proposed measures of specifically biological information are also problematic. For example, the key to the measure of information proposed by Gatlin (1972) is a deviation from the most random distribution. In theory, the absence of selective forces acting on the formation of nucleic acids and proteins is thought to bring about a highly random configuration, any deviation from it responding to a selective bias. Several difficulties arise here.

First, the measure does not allow for any distinction between deviations produced by the effects of natural selection and those derived from prebiotic conditioners (Wicken, 1987). There is also the conceptual problem whereby, according to Gatlin's formulæ, information increases along with redundancy, which ultimately leads to the absurd situation of maximum information with maximum redundancy. Gatlin keeps the functional meaning of information while restricting biological functions to the production of copies. Increased redundancy favours this function, but if this were the only tendency in evolution, the complexity of living things would not have increased. The limit imposed on the growth of redundancy is based on the need to perform (with competitive success) a series of bodily functions that are not strictly reproductive. Therefore, biological information cannot generally be identified with redundancy. The measure of information suggested by Brooks and Wiley (1986) has the same problem as Gatlin's.

In line with the concept of information and precisions mentioned, I shall now establish a measure of information as a function of the magnitude of its effects, that is, a change in knowledge. This measure is inspired by the ideas of Peirce and Popper, as well as by those of Mackay (1969), Dretske (1981), and Wicken (1987, 1988). The basic requirements of such a measure are that it agree with our intuitive notion of information and be coherent with the best theory of syntactical information available—Shannon's. Concerning the first condition, Dretske (2007) writes: "In formulating a theory of information we respect ordinary intuitions about what information is – and why else would one call it a theory of information" (p. 2)? The importance of the second requirement may be demonstrated by quoting Weaver (Shannon and Weaver, 1949):

> It seems clear that an important contribution has been made to any possible general theory of communication [...] It is almost certainly true that a consideration of

> communication on levels B and C will require additions [...] but it seems equally likely that what is required are minor additions and not real revision. (p. 26)

Here, the main thesis is that information can be considered as a (functional or pragmatic) relationship between a receiver, R; a message, m; and a system of reference, S:

i) a message, m_i, is an element of a set of alternative messages, M. So,

$M = \{m_1, m_2, \ldots, m_n\}$

ii) S can be any system and $\sigma = \{s_1, s_2, \ldots, s_q\}$ is a set of alternatively accessible states of S.

iii) R is characterized by:

iii.i) a set of (a priori) probabilities associated with the different alternative states of the referential system: $P(s_1), \ldots, P(s_q)$, where $\Sigma_k P(s_k) = 1$.

iii.ii) a function assigning an (a posteriori) probability, $P(s_k \mid m_i)$, to each pair $<m_i,s_k>$; where $\Sigma_k P(s_k \mid m_i) = 1$.

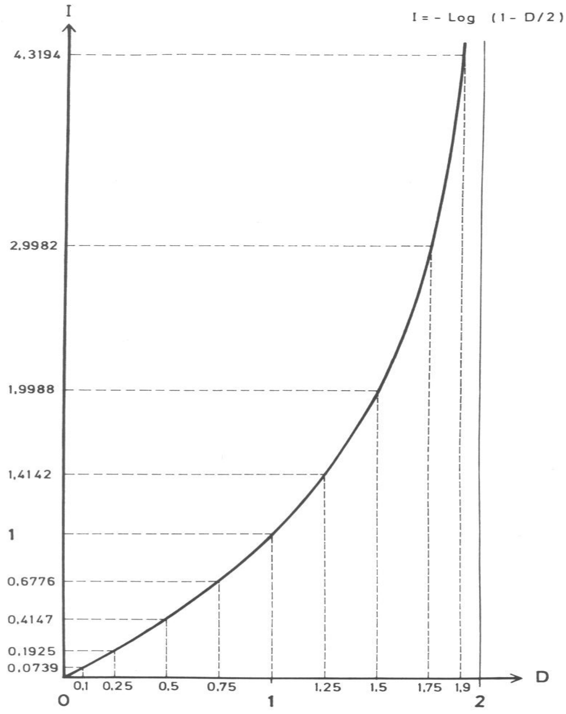
Information of m_i-to-R-about-S can therefore be measured by taking into account the difference, D, between the probabilities before the reception of the message, $P(s_1), \ldots, P(s_q)$ and afterwards, $P(s_1 \mid m_i),\ldots,P(s_q \mid m_i)$:

$D_{(m_i, R, S)} = \Sigma_k \mid P(s_k)-P(s_k \mid m_i) \mid$

Accordingly, we propose a measure of information in function of the binary logarithm of D (see Figure 2):

$I_{(m_i, R, S)} = -\log (1-(D/2))$

Figure 2:



We can find the average of information from M-to-R-about-S by weighting the information that each m_i carries with its frequency:

$I_{(M, R, S)} = \Sigma_i P(m_i) \bullet I_{(m_i, R, S)}$

It is possible and trivial to prove that: $0 \leq D \leq 2$

Therefore:

if $D = 0$, then $I = 0$

if $D = 2$, then there is no real value to I if $0 < D < 2$, then the amount of information, I, approaches ∞ when D approaches to 2

D=0 means that there is no change in R's knowledge of S despite his receiving the message, m_i, in which case, information, I, logically equals zero.

D=2 only happens if the message m_i informs of something happening that R previously considered impossible. In this case, our measure, I, has no real value, a situation where a radical restructuring of the subject's expectations is seen to be required. The receiver used so far by the subject has been surpassed, and an alternative one, if possible, must be found. We could therefore now assess the quantity of information in relation to a (meta)receiver dealing with second-order alternatives. For example, a statement considered literally impossible, such as "man is a wolf to men", would invite a metaphorical interpretation. The information rendered by this statement in relation to our –let us call- *literal receiver* has not real value, instead it has a positive value in relation to our *metaphorical receiver*. In addition, we have obtained some positive amount of information in relation to a receiver dealing with second-order alternatives, such as literal/metaphorical interpretation, as we now realize that the statement in question requires a metaphorical and not a literal interpretation.

This case is important because all learning processes (biological and cultural evolution, Piagetian development of cognitive structures, Kuhnian dynamics of scientific theories, etc.) seem to involve two kinds of change: accumulative or gradual (assumed within the limits of a given receiver and rendering a positive amount of information), and reorganizational or saltational (when our measure yields no real value, indicating that a radical change –a change to a new receiver- is required).

As Piaget observed, a little child believes that two containers of the same height can contain the same amount of liquid. The child uses a receiver in which the height of the liquid in the container is strictly correlated with the total amount of liquid. Nevertheless, disappointment about these expectations arrives sooner or later. Then, if the child's intelligence follows a normal development, he suffers a change in his worldview and shifts to another receiver. For this new receiver the total amount of liquid in a container depends on the container's volume, and not simply on its height. This step in learning development is an abrupt one preceded by a radical frustration regarding previous expectations.

In the field of the history of science, according to the perspective defended by Kuhn, we can also distinguish periods in which new data are accommodated into an existing paradigm -in our terms, they render information in relation to a certain receiver-, followed by others in which traditional expectations are broken and a shift to a new paradigm is required. We can say, then, that a change of receiver is felt as necessary by some part of the scientific community.

Evolutionary phenomena, like species extinction, are understood also as the raising of new environmental circumstances breaking the expectations incorporated into a given kind of organism. In informational terms, we can say that new messages seem to frustrate the expectations of the receiver currently used by an organism. If no organism of a species has the ability to use a different receiver, the extinction necessarily comes. However, if part of the species population, by chance, had already another suitable alternative receiver, then this part could survive.

I believe that our measure of information will help to capture formally all this intuitions.

In the other cases, our measure, I, approaches ∞ if D approaches to 2. This means that the greater number of possible states of the system and the greater the disagreement with R's previous knowledge (without reaching D=2), then the greater the amount of information (see Figure 1). Such results are obviously coherent with our intuitive notion of information.

Under certain restricted conditions, however, our formulæ can be demonstrated to yield the same outcomes as the standard Shannonian ones. In the classical theory of information, the amount of information produced by an event is measured by its probability. But can it be reduced to a three-element framework? What does m_i give information about? We may consider that the classical theory of information deals with systems giving information about themselves to receivers of this type:

	s_1	...	s_k	...	s_q
m_1	1	0	0	0	0
...	0	1	0	0	0
m_i	0	0	1	0	0
...	0	0	0	1	0
m_n	0	0	0	0	1

$q = n$

$s_k \equiv m_i$ *iff* $k = i$

$P(s_k) = P(m_i)$ *if* $k = i$

$P(s_k|m_i) = 1$ *iff* $k = i$

$P(s_k|m_i) = 0$ *iff* $k \neq i$

where

$D_{(m_i, R, S)} = 2\text{-}2P(s_k)$

Therefore:

$P(s_k) = 1\text{-}(D/2)$

Whence:

$I_{(m_i, R, S)} = -\log P(s_k)$

$I_{(M, R, S)} = -\Sigma_k P(s_k) \bullet \log P(s_k)$

That is, under certain restricted conditions ($M \equiv \sigma$), our formulæ for $I_{(m_i, R, S)}$ and $I_{(M, R, S)}$ yield the same outcomes as the standard Shannonian ones:

$I(m_i) = -\log P(m_i)$

$H(M) = -\Sigma_i P(m_i) \bullet \log P(m_i)$

In Shannon's terms, $I(m_i)$ is the information attributed to a message (m_i), and $H(M)$ is the entropy of a source. So, for Shannonian sources of information, that is, souces informing about themselves to a receiver of the type described above, the equations

$I_{(m_i, R, S)} = I(m_i)$

and

$I_{(M, R, S)} = H(M)$

are fulfilled.

Our measure of information meets the two basic requirements mentioned previously, as we have demonstrated that it is in accordance with our intuitive notion of information and clearly connected with Shannon's theory. It is also of some interesting use in biological contexts, as I shall attempt to show bellow.

In order to clarify how our measure works, I offer an (oversimplified) biological example:

i) Let the message, m_i, be a codon in a mature mRNA sequence being processed by a given ribosome, for example, the codon UCG. Let M be the set of all possible codons, so M = {UUU, UUC, …, GGA, GGG}.

ii) Let S be the next possible step in the peptide chain being synthesized by a given ribosome. In this case, a state of the system, s_k, should be considered the ribosome adding a given amino-acid to the chain or stopping the synthesis. So, σ = {Phenylalanine, Leucine, Serine, Tyrosine, …, stop,…, Glutamic acid, Glycine}.

iii) Let R be a functional cytoplasm with a random supply of amino-acids. R is characterized by**:**

iii.i) a set of (a priori) probabilities associated with the next possible step in the peptide chain:

- P(phe) = P(leu) = P(ser) = P(tyr) =, ..., = P(stop) =,…, = P(glu) = P(gly) = 1/21 = 0.047619

iii.ii) a function assigning an (a posteriori) probability. For the sake of argument, let us assume the following values:

- P(phe | UCG) = P(leu | UCG) = P(tyr | UCG) =, …, = P(stop | UCG) =, …, = P(glu | UCG) = P(gly | UCG) = 0.001
- P(ser | UCG) = 0.999

Whence:

$D_{(m_i, R, S)} = \Sigma_k \mid P(s_k)-P(s_k \mid m_i) \mid = 1.883761$

Accordingly, the information that the codon UGC gives to the cytoplasm's receiver on the next step that a given ribosome should take during the current process of synthesis is:

$I_{(m_i, R, S)} = -\log (1-(D/2)) = 4.1$ units of functional information (UFIs)

This quantity could vary, obviously, if we change any of the *relata* of the informational relationship, and there is no sense in attributing the amount to any particular *relatum*. So, the same genetic message could yield a different quantity of information when related to another kind of cytoplasm, as it is well known in the fields of transgenic engineering and developmental biology (see Alberts, 2002). For instance, a genetic fragment codifying for haemoglobin in an erythrocyte becomes mute in a neuron; the same protein in the same organism could perform different function in different kind of cells (Gilbert & Sarkar, 2000); and a signal pathway effector may lead to the induction of different gene products in different gene lineages (Brisken *et al*, 2002). Even more, the same genetic message could render more or less information to the same cytoplasm if we ask for any other biological function as the referential system. One could ask for the information that a codon gives to a certain cytoplasm on the syntheses of a functional protein. It is the case many times that an amino acid can be replaced by another one in a protein without any loss of functionality (see Salemi & Vandamme, 2003; Nelson & Cox, 2004). This is one of the reasons because we can find a considerable degree of genetic variability in natural populations. So, the a priori probability of synthesizing a functional amino acid is higher than the probability of synthesizing a given amino acid, like serine. In consequence, the amount of information, on the average, produced by *the same* codon to *the same* cytoplasm is higher regarding the synthesis of a given amino acid than regarding the synthesis of any functional amino acid.

Bioinformation revisited

Bioinformation and thermodynamic entropy

Information first comes to biology in connection with the concept of physical entropy and its different measures (thermodynamic or statistic). This well-known history begins with Clausius (1822-1888) and Boltzmann (1844-1906), who formulated the measures of entropy. Clausius was the first in introducing the term entropy to the thermodynamics in 1876. Boltzmann gave a statistical interpretation to the term. He considered that a macrostate of a given system is more entropic in the same measure as it is compatible with a greater number of microstates. The classical example is that of a box with a gas. The box has two compartments connected by a door. The system can be in a macrostate A, in which the temperature in one compartment is relevantly higher than in the other one, or in a macrostate B, with a uniform temperature. The macrostate A has a lower statistical probability because is compatible with less microstates than B. Boltzmann proposes the following formula for measuring entropy:

$S = K \text{ Ln } W$

where S is the entropy of a macrostate of a system, K is the Boltzmann's constant, and W is the number of microstates compatible with the macrostate. As it can be easily observed, this equation is similar to the shannonian formula for informational entropy.

Maxwell (1831-1879) took the next step with a thought experiment. If we place inside the box a demiurgic being who lets the quick particles pass to one compartment and the slow ones to the other, then the system evolves toward a less entropic state. Apparently this situation is incompatible with the second law of thermodynamics.

Leo Szilard (1898-1964) found a sound answer to Maxwell's paradox. The Maxwell's demon overcomes the universal tendency to entropy thanks to the information he obtains about the speed of the particles. However, he has had to measure the speed by means of whatever process which supposes surely the transaction of energy and the increase of entropy.   It seems that an (inverse) link exists between entropy and information.

Taking inspiration from this idea, Brouillin (1889-1969) developed the concept of *negentropy*, or negative entropy, as equivalent to information. More recently, we find Evans', Layzer's, and Frautschi's attempts to equate information with a positive magnitude, the distance from thermodynamic equilibrium (see Brillouin, 1962; Tribus, Sahnnon & Evans; Frautschi, 1982; Brooks &Wiley, 1986; Wicken, 1987; Weber, Depew & Smith, 1988; Layzer, 1990; Marcos, 1991).

The last step before the irruption of the concept of information in biology was the Schrödinger's (1944) classic *What is Life?*, whereby living things overcome the universal tendency to entropy by exporting entropy to their environment, as Maxwell's demon does. Thus is opened a connection between the thermodynamic order and biological complexity. Schrödinger contributes to the link between biological phenomena and physical entropy, and physical entropy had already been connected with information, so the path was ready for the encounter of information and biology. A slogan for this approach applied to biology could be “A gain in (physical) entropy means a loss of (biological) information.”

From the point of view proposed here, thermodynamic entropy conditions the information that the macrostate of a system can offer about its possible microstates to a receiver equipped with the right physical laws. If the particles of the system act together, the system as a whole is more dynamic. Correspondingly, the movement of the system offers a great deal of information about its elements. If entropy increases, the system is less dynamic and, furthermore, reflects less efficiently the positions and moments of its components. Thus, Thermodynamic entropy is linked *specifically* with the information that a macrostate can give about a system’s currently accessible microstates. So, the basis for a general measure of information could not be entropy, negentropy or distance from equilibrium (Marcos, 1991).

Physical entropy is currently linked with (structural) order and (functional) organization, but order and organization are respectively relative to a structure and a function. Several types of order or organization may be identified even within the same system. Organization is also relative to a receiver connecting the message and the system of reference. A fragment of DNA is organized for the synthesis of a certain protein only if one knows how the cellular apparatus works. Physical entropy, therefore, should not be considered a general measure of organization—it is a correct approach to *one* type of organization able to render work (Denbigh, 1985; Nauta, 1972). In biology, organization is always established with regard to a certain function. It is not just a question of structural regularity. This is why Schrödinger (1944) conjectured, before the discovery of the double helix, that genetic information must be contained in some kind of *aperiodic* crystal. Our concept and measure of information can bring us nearer to an estimation of biological organization than mere negative entropy. Furthermore, as we have seen, they facilitate a reasonable interpretation of the link between physical entropy and information.

Bioinformation and Shannon's entropy

Chronologically, the next relevant domain is the transmission of signals. Here, the decisive contribution was Shannon's mathematical theory of communication, but Nyquist and Hartley may be mentioned as precedents. From this perspective, information is contemplated as surprise or uncertainty. There is a formal connection between physical entropy (Boltzmann's entropy) and information entropy (Shannon's entropy), as von Neumann first noted. Although they both conform to the same formal schema, however, there is no reason why their behaviour should follow the same laws (Marcos, 1991).

The relation between Shannon's entropy and information as a triadic relation has been dealt with above, including in mathematical terms, but some remarks are in order here. On the one hand, the structure of the system the message belongs to affects the information, but in the opposite way to that of the system of reference. When we try to pass information, we do not want the system to which the message belongs to impose any structural limitations on our communication, or at least we want them kept to a minimum. This is what Shannon calls *entropy* (freedom of choice within a source), and is recommended for a system acting as a symbolic one. This is why in some parts of biological systems, for example in neuronal, genetic, immunological, and linguistic domains, unities can be combined in many different ways, for they must be flexible when representing other parts of the systems or external realities.

On the other hand, a higher level of structure, form, organization, or regularity in the system of reference brings about the possibility of transmitting more information about it, in line with common sense and philosophical tradition (Eco, 1962; Moles, 1972). Consequently, this matter is sometimes shrouded in confusion. It could be seen as a paradox that some authors correlate positively information with freedom of choice or low structural constraints, as Shannon does, while others, like Eco and Moles, correlates information with structural order, constraints or regularity . But it is not paradoxical at all. One thing is the relative order of the system of reference and another is that of the symbolic system. Shannon's entropy of the symbolic system correlates positively with information, while in the object that the system informs about, the greater the order and organization, the more information could be produced.

Finally, another factor limiting the amount of information is the correlation between the structure of the message and that of the referential system. If it is perfect, a maximum amount of information can be transmitted. No greater correlation exists than between a system and itself. In this regard, Shannon's measure is an absolute limit on the amount of information: no more information can be given about a system than is given by the system itself. Therefore, Shannon's measure is often referred to as a measure of possible information.

Bioinformation and complexity

Another approach to information appeared recently, based on the work of Kolmogorov (1965) and Ray Solomonoff (2003): the algorithmic or computational theory. Here, information is viewed as a special kind of complexity. Any sequence describing a text, image or music, etc., may be generated by means of a program and a suitable computer. If the sequence shows any regularity, symmetry, or redundancy, the program could be shorter than the sequence itself. If the sequence is more *complex*, or even chaotic, it will be less susceptible to compression, so the greater the complexity, the lesser the compressibility. Moreover, a general measure of complexity can be obtained by taking a universal Turing machine as the relevant computer, in which case a triadic relation could easily be detected: the algorithm or program is a message to a receiver based on the universal Turing machine, on a system of reference: the compressed sequence.

It must be remembered that information, unlike complexity, is not a property of a single thing, but a relation between at least three entities, so some remarks may be made on the relationship between Kolmogorov's complexity and bioinformation. First, the relationship between information and the complexity of a sequence is not a direct one, that is, complexity cannot be simply equated with information. The need for a long program to generate a sequence does not translate directly into that sequence "having" a great deal of information. It would be counter-intuitive, for chaotic sequences would be the most informational ones. Kolmogorov's measure of complexity can distinguish between a crystal and a protein, but a relevant concept of bioinformation must also distinguish between a functional protein and a random peptidic compound.

Second, Kolmogorov's notion of complexity has also been used to calculate the informational content of an individual object as a direct function of the length of the shortest program describing or producing it. Here we must remember the difference between things and words. When complexity is assessed from the compressibility of a description codified in a binary sequence, it could normally be referred to a universal Turing machine. The input into such a computer is a binary sequence, as is the output, so the computer cannot relate the description to the object itself. Therefore, a measure of the complexity of sequences is available, but this does not mean that we can calculate the complexity of the object described, because the information that a description gives about an object is always referred to a certain receiver in a concrete subject. For example, a DNA sequence is a good description of the three-dimensional structure of a protein *to certain cytoplasmic machinery*, but it would not make sense to say that it is generally, or for a Turing machine (see Rosen, 1985).

Third, there are doubts as to whether natural selection can explain the increase in complexity throughout evolution (Marcos, 1991a, 1992). After all, organisms exist that are very simple but seem perfectly adapted, a classic objection to Darwinism (Bertalanffy, 1968). The connection we have established between complexity and information may clarify the issue. Later variants in evolutionary succession may "take into account" those already existing, but not vice versa (Darwin, 1859; Rosen, 1985). Once an organism A is settled into its environment, any other organism B will adapt to this environment more effectively if it is equipped to relate informationally with A. This informational asymmetry means that both the environment and organisms become more and more complex, and so maintain their adaptational dynamics throughout evolution. In this regard, complex systems could be indicative of a complex environment, for more information is required to adapt to a complex environment than to exist in a simple one. The existence of living beings that adapt to an environment in which others already exist may ensure the survival of the latter, rather than threaten it, since the environment to which the new system adapts is also that on which they depend. Humanity's acceptance of this idea is not unconnected with the increase in ecological awareness.

Bioinformation and meaning

Information is intuitively linked with meaning, so some authors have considered some development of the theory of information necessary to understand this connection (Bar-Hillel, 1964; Hintikka & Suppes, 1970; Hintikka, 1973; Perry and Barwisse, 1983; Hanson, 1990; Villanueva, 1990; Barwise & Seligman, 1997; Seligman, 2007). Carnap, Bar-Hillel, and Hintikka's basic idea is that the more a statement prohibits, the more it says. The way of measuring this magnitude is as follows: we take a limited formal language and give equal probability to all the syntactically possible combinations of its elements; then we take a correct statement and the class of all its logical consequences. Now, some grammatically correct statements may be forbidden in this class, so the probability of the others increases. The amount of information (a number), therefore, is a function of the number of prohibited statements, and the informational content (a class) depends on the statements still in play. It will be observed that contradictory statements would, somewhat counterintuitively, have the maximum content.

Even this approach could be reduced to a triadic relation scheme: the system of reference is the set of grammatically correct combinations of symbols. The message is the statement under consideration and we then need, in the words of Bar-Hillel (1964): "a receiver with a perfect memory who ‘knows’ all of logic and mathematics, and together with any class of empirical sentences, all their logical consequences” (p. 224). An ideal receiver is, of course, a receiver, and Bar-Hillel proposes treating his theory as an ideal pragmatics.

All that we can say is that the difference between linguistic and non-linguistic information lies in the nature of the link between the message and the system of reference. In one case it is conventional and in the other natural. There is a natural link of cause and effect between fire and smoke (Devlin, 1991), but the link between spirals of smoke and taking up the hatchet is conventional (Kampis and Csányi, 1991; Kampis, 1990). I would stress, however, that between a direct or strictly natural causality and a purely conventional nexus, there may be a zone of transition (see Millikan, 1989), as we can see in biological contexts.

Bioinformation and knowledge

Information is also related to knowledge. Dretske (1981) defines information as “a commodity that, given the right recipient, is capable of yielding knowledge” (p. 47). So a triadic relation is also needed here: we have the message, the circumstances it informs about and the “right recipient.” Information is therefore related to knowledge in a dual way: it depends on the receiver's previous knowledge, while knowledge is an effect produced by information, at least a change in the receiver and at best a change in the receiver as regards the real state of affairs (see Dretske, 1981). So, knowledge itself can be viewed as the property of a subject (edification) or as a dyadic relation between subject and object (correspondence, correlation). It is easy to connect the first notion of knowledge with biology: bioinformation contributes to the construction of living beings themselves. It is more difficult to apply the demand for truth. Nevertheless, I think that even in biological contexts information somehow requires truth.

Bioinformation location: Places and levels

Where is bioinformation? In my opinion, a relative notion and measure of information could avoid the (pseudo-)problem of finding the location of bioinformation. It could be (dis)solved by considering information, not as being already present somewhere (in the genes, cytoplasm, proteins, environment, ecosystem, brain, or wherever) but as being established by interactive relations.

The functioning of any living system (or part of a living system) depends on various factors. For example, the three-dimensional structure of a protein depends on DNA, but also on the very "machinery" of the cell. What the message is and what the receiver is are chosen conventionally but not arbitrarily. A message is usually defined as a small factor of great specificity in relation to a given function and displaying a high potential for variability. The DNA codifying a certain protein possesses these characteristics in relation to the function of synthesizing the protein in question, and the protein in relation to its biological function. In other words, the slightest alteration of the DNA could destroy the structure of the protein, and the slightest change in a protein could destroy its function.

Such an effect is unlikely to be the result of a similar change in an environmental factor. But this does not force us to identify the information with a property of the message. The information in a fragment of DNA about a protein obviously depends on its specificity, but only regarding a given receiver (Sattler, 1986). Actually, the probability of any given protein arising in a prebiotic environment (Yockey, 1977, 1981), even in the presence of a specific DNA, is minimal. Therefore, information is located neither before nor after the triadic relation. Kampis and Csányi (1991) state: “we have to give up the idea of a complete localization of information” (p. 23).

On the other hand, any one fragment of DNA may, of course, produce information on more than one function, and not necessarily in the same quantity. For example, attempts could be made to calculate the amount of information in a fragment of DNA in relation to the transportation of oxygen, which is different from the function of producing a particular protein. The difference lies in the fact that the same function can be performed by different proteins or variants of a protein. This phenomenon of “synonymy” must not be ruled out from calculations on information.

Finally, let us deal very briefly with the location of information in living systems according to different hierarchical levels (Collier, 2003). For all intents and purposes, in the absence of connecting principles, the amount of information obtained by an external observer, for example a scientist, on a living system at different levels should be considered as amounts of information about different systems. Otherwise, more information would supposedly be derived about a living being from the knowledge of, for example, its atomic state than of its genetic makeup (see Atlan, 1972). Information on the atomic state is not about the living being *per se*, unless we have theoretical principles connecting atomic states with some functional characteristics. Developing principles of connection between levels is like developing a receiver that allows us to obtain information about one level from another acting as a message. This touches on the philosophical question of epistemological reductionism. We know that, given certain principles of connection, one biological level can inform us about another, but we also know that a complete reduction is not viable, for any concrete informational relation is subject to imperfections.

Concluding Summary

The concept of information has become one of the central ones of our civilization, so much so that we call our society an "information society." The life sciences have been affected by this movement. Biology has developed what we might call an *informational paradigm*. Recently, a debate has arisen on the usefulness of this informational perspective in biology (Griffiths, 2001; Queiroz, Emmechec & El-Hani, 2007).

As I have sought to establish, the understanding of many biological processes in terms of information is certainly useful and clarifying, but provided the very concept of information is submitted to scrutiny. It is necessary to find clarity concerning the very notion of information, to derive therefore a measure that is significant in biology and to clarify also the relationships between the concept of information and others akin to it commonly used in different biological theories. I tackled this task by presenting the outline of a theory of information.

First, I presented a concept of information as a triadic relation involving a message, a receiver, and a system of reference. The effect produced by this relation is a variation of the knowledge that the receiver has of the system of reference. Knowledge is understood in the wide sense, which does not require consciousness, and which is applicable to any living system and indeed to certain artefacts. From here, we have developed a measure of information as a function of the magnitude of the change of knowledge produced by a given informational relation. I have shown that the results of this measure are coherent with our pre-theoretical intuitions and that our measure of information may be formally linked with Shannon's.

Finally, I sought to clarify the relationship of the notion of information as a triadic relation with others that are also important in biology, like entropy (thermodynamic and informational), complexity, order, organization, meaning, and knowledge. The same concept of information as a relation has allowed us to tackle the recurring debate on the location of biological information. As it is a relation, it does not make sense to locate information before or after the informational relation in either a concrete place in living systems or their environment, or on a definite hierarchical level of biological organization.

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Figure 1. Schematic diagram of a general communication system (Shannon & Weaver, 1949, p. 34)

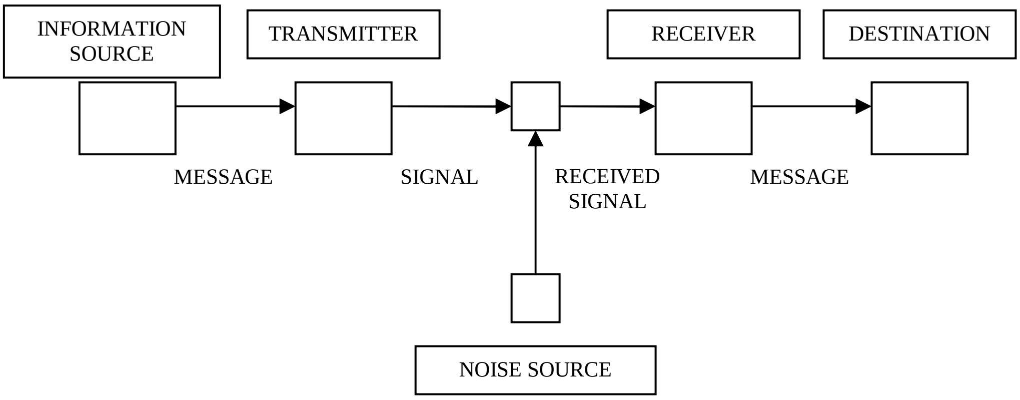

Figure 2. Information measure, I, in function of the binary logarithm of D