Semiotic modelling of biological processes: an introduction to Peircean semiotics

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General abstract: Here we introduce biosemiotics as a field of research that develops models of life processes focusing on their informational aspects. Peirce's general concept of semiosis can be used to analyze such processes, and provide a powerful basis for understanding the emergence of meaning in living systems, by contributing to the construction of a theory of biological information. Peirce's theory of sign action is introduced, and the relation between 'information processing' and sign processes is discussed, in fact, a semiotic definition of information is introduced. Three biosemiotic models of informational processes, at the behavioral and molecular levels, are developed, first, a model of genetic information processing in protein synthesis; second, a model of signal transduction in Bcell activation in the immune system; and, finally, a model of symbolic non-human primate communication. We also address some perspectives for the development of applied semiotic research in fields such as Artificial life, cognitive ethology, cognitive robotics, theoretical biology, and education.

In this lecture, we introduce theoretical notions one must consider to face the main problems on modeling biological information processes.

1. Peircean semiotics: a very brief introduction

Peirce is often considered the founder of modern semiotics.[1] Semiotics was defined by Peirce (CP 5.484) as "the doctrine of the essential and fundamental nature of all varieties of possible semioses". In other words, semiotics describes and analyses the structure of semiotic processes independently of their material bases, or of the conditions under which they can be observed – inside cells (cytosemiosis), among tissues and cell populations, in animal communication (zoosemiosis), or in typically human activities (production of notations, meta-representations, etc.). In other words, Peirce's concept of semiotics concerns a theory of the sign in its most general sense. Peirce conceived general semiotics much like a formal science as mathematics is (CP 2.227). However, semiotics finds the objects of its investigation in the signs' concrete, natural environment – and in 'normal human experience', or, else, in 'ordinary experience' (Potter 1967: 8; CP 1.241).

Semiotics is subdivided into speculative grammar, critical logic, and speculative rhetoric (CP 2.229). The first division of this science is what interests us here. Its task is that of examining the 'sign physiology of all kinds' (CP 2.83), that is, the concrete nature of signs as they emerge and develop, and the conditions that determine the signs' further development, nature, and interpretation. It is the

[1] Following a scholarship tradition, Peirce's works will be referred to as CP (followed by volume and paragraph number) for quotes from *The Collected Papers of Charles S. Peirce* (Peirce, 1866-1913); EP (followed by volume and page number) for quotes from *The Essential Peirce* (Peirce, 1893-1913); MS (followed by the number of the manuscript) for quotes from *The Annotated Catalogue of the Papers of Charles S. Peirce*; and SS (followed by page number) for quotes from *Semiotic and Significs: The Correspondence between Charles S. Peirce and Victoria Lady Welby*.

branch that investigates: (i) the conditions to which any and every kind of sign must be submitted, (ii) the sign itself, and (iii) its true nature (CP 1.444). As part of its tasks, speculative grammar elaborates on the 'classifications of signs' or, in other words, the diversity of sign types and how they merge with one another to create complex semiotic processes. For Houser (1997:9), "the logician who concentrates on speculative grammar investigates representation relations (signs), seeks to work out the necessary and sufficient conditions for representing, and classifies the different possible kinds of representation". Peirce developed, between 1867 and 1911, a model of signs as processes, actions, relations, and also elaborated divisions of signs in order to describe different kinds of semiotic processes.

Peirce's pragmatic model of meaning as the "action of signs" (semiosis), has had a deep impact (besides all branches of semiotics) on philosophy, psychology, theoretical biology, and cognitive sciences (see Freeman 1983; Fetzer 1997; Colapietro 1989; Emmeche & Hoffmeyer 1991; Tiercelin 1995; Hoffmeyer 1996; Debrock 1996; Deacon 1997; Houser 1997; Hookway 1985, 2002; Freadman 2004; Queiroz & Merrell 2005; Pietarinen 2006; Short 2007). First and foremost, Peirce's semiotics is grounded on a list of categories – Firstness, Secondness, Thirdness – which corresponds to an exhaustive system of hierarchically organized classes of relations (Houser 1997). This system makes up the formal foundation of Peirce's philosophy (Parker 1998) and his model of semiotic action (Murphey 1993: 303-306).

In brief, the categories can be defined as follows: (1) Firstness: what is such as it is, without reference to anything else; (2) Secondness: what is such as it is, in relation with something else, but without relation with any third entity; (3) Thirdness: what is such as it is, insofar as it is capable of bringing a second entity into relation with a first one in the same way that it brings itself into relation with the first and the second entities. Firstness is the category of vagueness and novelty: "firstness is the mode of being which consists in its subject's being positively such as it is regardless of anything else. That can only be a possibility" (CP 1.25). Secondness is the category of reaction, opposition, and differentiation: "generally speaking genuine secondness consists in one thing acting upon another, — brute action. […]. I consider the idea of any dyadic relation not involving any third as an idea of secondness" (CP 8.330). Finally, Thirdness is the category of mediation, habit, generality, evolution and conceptualization (CP 1.340).[2]

2. Semiosis, meaning and the action of sign

According to Peirce, any description of semiosis should necessarily treat it as a relation constituted by three irreducibly connected terms (sign-object-interpretant, S-O-I) (CP 2.171, CP 2.274) (Figure 1) — we will hereafter refer to these terms of a triadic relation as S, O, and I.

Peirce conceived a 'Sign' as a 'First' which stands in such a genuine triadic relation to a 'Second', called its 'Object', so as to be capable of 'determining a Third', called its 'Interpretant', to assume the same triadic relation to its Object in which

[2] For further discussion of the categories, see Hookway (1985), Murphey (1993), Potter (1997), Short (2007).

it stands itself to the same Object (CP 2.274. See also CP 2.303, 2.92, 1.541). The triadic relation between S, O and I is regarded by Peirce as irreducible in the sense that it is not decomposable into any simpler relation. Accordingly, the term 'sign' was used by Peirce to designate the irreducible triadic process between S, O and I, but he also used it to refer to the first term of the triad. Some commentators have proposed that we should distinguish between the 'sign in this strict sense' (representamen, or sign vehicle), when referring to the first term of the triad, and the 'sign in a broad sense' (or sign process, sign as a whole) (e.g. Johansen 1993: 62).

In Peirce's definitions of sign, we find several clues to understand how signs act. Any sign is something that stands for something else, its object, in such a way that it ends up producing a third relational entity, an interpretant, which is the effect a sign produces, in the context of biosemiotics, in an interpreter (a biosystem such as a cell or an organism). In many biological informational processes, sign interpretation results in a new sign within the interpreter, which refers to the object as the former sign refers to the same object, or ultimately in an action, which can lead to the termination of an informational process. That the interpretant is often another sign, created by the action of a previous sign, is clear in the following statement by Peirce: A sign is "anything which determines something else (its interpretant) to refer to an object to which itself refers (its object) in the same way, the interpretant becoming in turn a sign, and so on, ad infinitum" (CP 2.303). Accordingly, it is important to bear always in mind that the interpretant is not necessarily the product of a process which amounts to 'interpretation' in the sense we use this term to account for human cognitive processes. The fundamental character of the interpretant in many biological processes is that it is a new sign produced by the action of a previous sign in such a manner that both may share the same object.

One of the most remarkable characteristics of Peirce's theory of signs is its processual nature. As a truly process thinker, it was quite natural that Peirce conceived semiosis as basically a process in which triads are systematically linked to one another so as to form a web (see Gomes et al., 2007). Peirce's theory of signs has a remarkable dynamical nature. The complex S-O-I is the focal-factor of a dynamical process (Hausman 1993: 72).

It is important to avoid losing from sight the distinction between the interpreter, which is the system that interprets the sign, and the interpretant. The interpreter is described by Peirce as a 'Quasi-mind' (CP 4.536), a description which demands, for its proper interpretation, a clear recognition of Peirce's broad concept of 'mind' (Ransdell 1977). It is not the case that only conscious beings can be interpreters in a Peircean framework. Rather, a transcription machinery synthesizing RNA from a string of DNA or a membrane receptor recognizing a given hormone can be regarded as interpreters. A basic idea in a semiotic understanding of living systems is that these systems are interpreters of signs, i.e., that they are constantly responding to selected signs in their surroundings. Thus, the interpreter does not have to be a conscious being, not even an organism, as it may be some part or subsystem within an organism, or a humanly-designed product. Nevertheless, since a sign process is itself an interpreter, the concept of interpreter appears to be secondary in Peirce's semiotics, even though it can play a

heuristic role in building some models of semiotic processes.

3. Sign as form communication

Peirce also defines a sign as a medium for the communication of a form or habit embodied in the object to the interpretant (De Tienne 2003; Hulswit 2001; Bergman 2000), so as to constrain the interpretant as a sign or the interpreter's behavior (Figure 1):

> "… a Sign may be defined as a Medium for the communication of a Form. [...]. As a medium, the Sign is essentially in a triadic relation, to its Object which determines it, and to its Interpretant which it determines. [...]. That which is communicated from the Object through the Sign to the Interpretant is a Form; that is to say, it is nothing like an existent, but is a power, is the fact that something would happen under certain conditions" (MS 793:1-3. See EP 2.544, n.22, for a slightly different version).

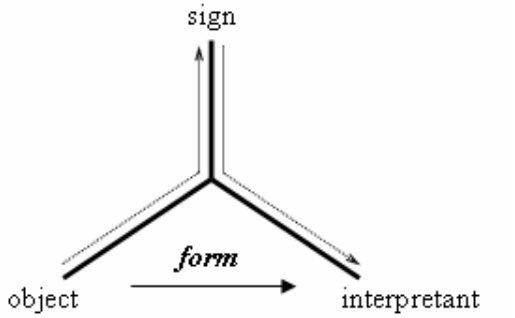

Figure 1: Semiosis as a relation between three irreducibly connected terms (sign-object-interpretant, S-O-I). This triadic relationship communicates/conveys a form from the object to the interpretant through the sign.

What is a Form? There is a movement in Peirce's writings from 'form as firstness' to 'form as thirdness'. Form is defined as having the 'being of predicate' (EP 2.544) and it is also pragmatically formulated as a 'conditional proposition' stating that certain things would happen under specific circumstances (EP 2.388). It is nothing like a 'thing' (De Tienne 2003), but something that is embodied in the object (EP 2.544, n. 22) as a habit, a 'rule of action' (CP 5.397), a 'disposition' (CP 2.170), a 'real potential' (EP 2.388) or, simply, a 'permanence of some relation' (CP 1.415).

Form can also be defined as potentiality ('real potential', EP 2.388). If we consider this definition, we will also come to the conclusion that form can show the nature of both firstness and thirdness. Consider that potentiality is not the same as mere possibility. For the sake of our argument, consider Peirce's treatment of Quality as a 'mere abstract potentiality' (CP 1.422). It is abstraction not in the sense of a reduction of complexity to formal simplicity, but in the sense that the quality in question has been 'abstracted' ('cut') from the continuum of possibilities.

Quality, then, has the nature of Firstness, being essentially indeterminate and vague. But we can also talk about a generality of Quality. In this case, we are beyond the domain of pure Firstness, since generality refers to some law-like tendency. Peirce works in this case with a merging of Firstness and Thirdness. As an

abstract potentiality, Quality is closer to a blend of Firstness and Thirdness, than to pure Firstness. Such a treatment seems to be compatible with Peirce's categorical scheme, since, as Potter (1997: 94) stresses, the categorical structure which Peirce uses is 'highly subtle and complex, admitting of various combinations'.

For Murphey, there is a transition from the notion of meaning as a qualitative conception carried by a sign to an inter-relational notion according to which the meaning of a concept consists in a 'law relating operations performed upon the object or conditions of perceptions to perceived effects' (Flower & Murphey 1977: 589). The qualitative conception involves reference to the sign's ground, while the 'law' or necessary conditions of perception are inter-relational rather than qualitative -- 'If the meaning of a concept of an object is to consist in the conditionals relating operations on the object to perceived effects, these conditionals will in fact be habits' (Flower & Murphey 1977: 590).

Here, we would like to stress that the form communicated or conveying from the object to the interpretant through the sign is not the particular shape of an object, or something alike, but a regularity, a habit which allows a given semiotic system to interpret that form as indicative of a particular class of entities, processes, phenomena, and, thus, to answer to it in a similarly regular, lawful way. Otherwise, the semiotic system would not be really capable of interpretation.

The communication/conveyance of a form from the object to the interpretant constrains the behavior of an interpreter in the sense that it brings about a constrained set of relations between the object and the interpretant through the mediation of the sign. We will understand the "meaning" of a sign, thus, as an effect of the sign - conceived as a medium for the communication/conveyance of forms - on an interpreter by means of the triadic relation S-O-I. *A meaning process can be thus defined as the action of a sign* (semiosis).

This brings about a constrained set of effects of the Object on the interpreter through the mediation of the Sign. In short, Peirce defines a Sign both as 'a Medium for the communication of a Form' and as 'a triadic relation, to its Object which determines it, and to its Interpretant which it determines'. If we consider both definitions of a Sign, we can say that semiosis is a triadic process of communication of a form from the Object to the Interpretant by the Sign mediation.

Semiosis necessarily entails the instantiation of chains of triadic relations (which we will abbreviate here as 'triads'), since a sign in a given triad will lead to the production of an interpretant, which is, in turn, a new sign. This property is highly relevant to our analysis. An interpretant is both the third term of a previous triad and the first term (sign) of a subsequent triad (Savan 1987. See Figure 2). Here, we have a first transition accounting for the dynamical nature of semiosis, namely, the interpretant-sign (I-S) transition. By this 'transition' we simply mean that the same element that plays in a triad the role of the interpretant will play in a subsequent triad the role of the sign. From a Peircean perspective, to perform sign processing and interpretation is to produce further (or, as Peirce says, more developed) signs. Nevertheless, there are cases in which a semiotic process ends up in the production of interpretants which are not signs, such as, for instance, actions in a living

system, say, the triggering of a given chemical reaction or a prey's behavior to escape from a predator. It is clearly the case that such a reaction or behavior can be signs for further interpretation, but that particular chain of signs which were taking place has indeed come to an end through that action or behavior, and these further interpretative processes must be modeled as another, new chain of signs. Peirce himself, after 1907, acknowledged that there are interpretants that are not signs, or, to put it differently, does not have the nature of a sign.

Please also remember that the outline in this section is logical (or semiotic) and that within a particular physical, chemical or biological system, the semiotic processes described here in general terms can be instantiated by different physical means, e.g., shifts in chemical concentrations or processes of molecular recognition. We will add this material aspect when we present two biosemiotic models below.

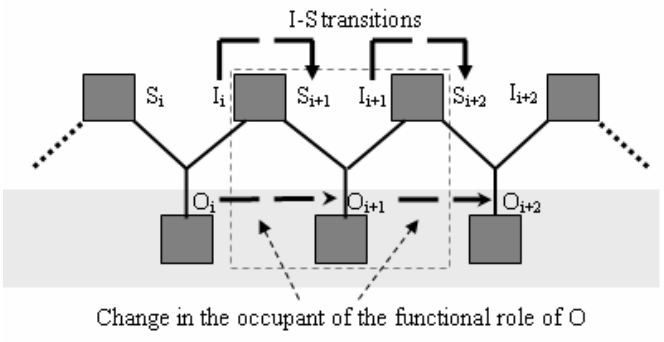

Figure 2: The triadic relation S-O-I forms a chain of triads. The grey area at the bottom of the figure shows that all signs in the chain of triads refer to the same dynamical object through a series of immediate objects. The arrows show the interpretant-sign (I-S) transition and the changes in the occupant of the functional role of the immediate object.

When the I-S transition takes place, there is also a change in the occupant of the functional role of the immediate object (Figure 2). When the interpretant becomes the sign of another triad, the relation of reference to the same dynamical object depends on the fact that the new occupant of the role of immediate object stands for the same aspect of the dynamical object that the immediate object of a previous triad stood for. Thus, an object turns to be a plural object via semiosis.

As Figure 2 shows, in a triad *i* a given sign S_i indicates a dynamical object by representing some aspect of it, the immediate object O_i. Through the triadic relation, an interpretant I_i is produced in the semiotic system. This interpretant becomes the sign in a subsequent triadic relation, S_{i+1}, which now indicates the same dynamical object. It should indicate this object through a new immediate object, which corresponds to an aspect of the dynamical object represented in the sign. We have now a new occupant of the role of immediate object that stands for the same aspect of the dynamical object which was represented in the previous sign, S_i. It is in this sense that there is a change in the occupant of the functional role of the immediate object, from O_i in a previous triad to O_{i+1} in a subsequent triad. Through the triadic relation, a further interpretant, I_{i+1}, will be produced, which will then become the sign in a new triad, S_{i+2}, and thus successively, up to the end of that specific sign process.

4. The subdivision of the object and the interpretant

We also need to consider here Peirce's distinctions regarding the nature of objects and interpretants (For a review of these topics, see Savan 1987-1988, Liszka 1990, Short 1996). He distinguishes between the immediate and dynamical objects of a sign as follows:

> "We must distinguish between the Immediate Object – i.e., the Object as represented in the sign – and [...] the Dynamical Object, which, from the nature of things, the Sign *cannot* express, which it can only *indicate* and leave the interpreter to find out by *collateral experience*" (CP 8.314. Emphasis in the original).

And we should also consider his distinction between three kinds of interpretants:

> "The *Immediate Interpretant* is the immediate pertinent possible effect in its unanalyzed primitive entirety. [...]. The *Dynamical Interpretant* is the actual effect produced upon a given interpreter on a given occasion in a given stage of his consideration of the Sign" (MS 339d:546-547. Emphasis in the original).

And:

> "... the Final Interpretant is the one Interpretative result to which every Interpreter is destined to come if the Sign is sufficiently considered. [...] The Final Interpretant is that toward which the actual tends" (Letter to Lady Welby, SS 110-1, 1909).

Let us consider, first, Peirce's distinction between the immediate and the dynamical objects of a sign. The immediate object of a sign is the object as it is immediately given to the sign, the dynamical object in its semiotically available form. That is, the aspect of the dynamical object that is represented in the sign is the immediate object, which amounts, thus, to the dynamical object as the sign represents it (this is what we mean by "semiotic availability'). Furthermore, the sign does not represent the dynamical object in its reality, but just indicates that object. The system which is causally affected by the sign (because it stands for something else to that system) should establish which dynamical object the sign indicates through processes that have been selected for in the evolutionary history of that kind of system. In the ontogenetic timescale, the system will acquire its semiotic competence, i.e., its competence as a sign interpreter, through development.

Peirce defines the dynamical interpretant as the actual effect of a sign, while the immediate interpretant is its 'range of interpretability' – the range of possible effects that a sign is able to produce (see Johansen 1993:166-167). The dynamical interpretant is, thus, the instantiation of one of the possible effects included in the immediate interpretant. The final interpretant in a semiotic process is, in turn, the final state of this process, understood as a tendency being realized when a given chain of triads is triggered, but not determined or bound to happen, since other final states can follow from the semiotic process, as in the case, for instance, of misinterpretation.

Peirce (CP 8.177) writes that a sign determines an interpretant in some 'actual' or 'potential' Mind (in other passages, a 'quasi-mind'. See CP 4.536). It is indeed

possible to differentiate between 'potential' and 'effective' semiosis. Potential semiosis is defined as a triadically-structured process which is not taking place, which is only in potency. Effective semiosis, in turn, is a sign in effective action, i.e., a sign which, by being actualized, has an actual effect on the interpreter.

In sum, according to Peirce's pragmatic model, semiosis is a triadic, dynamic, time-bound, context-dependent (situated), interpreter-dependent (dialogic), materially extended (embodied) dynamic process. It is a social-cognitive process, not merely a static, symbolic system. It emphasizes process rather than product.

5. Concluding remarks

The framework for building a theory of biological information presented here is consistent with the general picture of genetic information and signaling processes in genetics and molecular biology [see Lecture V], with the fundamental difference that, first, a concept of information is explicitly formulated within a heuristically powerful theoretical framework, and, second, it is on these grounds conceptualized as a process. Consequently, to make this semiotic framework and the current structure of genetics and molecular biology compatible, it is necessary to conceive the latter in more process-oriented terms. This is a fruitful avenue to be pursued in order to build a framework for biology that is more compatible with the increasingly complex and dynamic nature of biological systems revealed by recent advances in the biological sciences (for some suggestions to the same effect, see, *e.g.*, Neumann-Held 2001, Keller 2005). We consider the compatibility of semiotic analyses with the framework of genetics and molecular biology as a strong feature. Nevertheless, it is open to investigation and evaluation the pros and cons of complementing the current models in genetics and molecular biology with a semiotic concept of information.

In the next lectures, we will argue that semiotic modeling is a necessary counterpart to functional and mechanistic models of genetic and signaling systems. The conceptual and methodological tools offered by Peircean semiotics can help to make more precise what constitutes information in biological systems. The development of biosemiotic models can be seen as a contribution to understand fundamental phenomena in biology which are described by a communicational and informational vocabulary. This is particularly important in a time in which biology is increasingly seen as a science of information. It is never too much to remind that we do not have an established general notion of biological information up to this point (despite the roles that the meaning-free concept of information offered by the mathematical theory of communication can play in biological research), and it is a basic contention of this work that biosemiotics can help in building a semantic/pragmatic concept of information processes.

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Next lecture **(Multi-level model of emergent semiosis)**

According to Peircean model of meaning process, semiosis is conceived as a systemic process at a focal level, in which chains of triads are instantiated as a result of the interaction between potentialities established by a micro-semiotic level (initiating conditions) and the regulatory, selective influence of a macro-semiotic level (boundary conditions).

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