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POINT OF VIEW

Von Neumann's Legacy for a Scientific Biosemiotics

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The notion of semantics has both concerned and eluded science since ancient times. The situation is radically different for the notion of syntax. Especially in the last century, what is syntax received an unambiguous answer: it is anything that can be captured by a Turing machine, that is, anything that can be computed. Syntax is whatever corresponds to the algorithmic (rule based) manipulation of symbols. However, as Gödel, Church and Turing showed, there is more to reality than syntax alone. In particular, however powerful and universal a syntactic system or formal model may be, there are always things that escape it, that is, of which the truth cannot be decided from within the system. So *something* is missing and, as Robert Rosen already noticed, this something has everything to do with semantics (Rosen 1991).

Church and Turing showed that syntax covers all computable functions, what could possibly be missing from such an encompassing set of things? In physics, reality is captured in terms of computable formulas, so it's theories reside in the realm of syntax. However, among all possible syntactic systems—there are an infinite number of them—only very few qualify as useful physical theories: only those that allow the physicist to control the outcome of actual, physical experiments. Thus, syntax is not too impoverished, in a very definite sense it is too powerful: A syntactic system *can* be useful, but only very few generally are. It appears that one thing that is missing is a criterion for usefulness.

So when is something useful? There is no answer to this question because it is ill posed. The concept of "usefulness" is inherently relational, it involves at least two things, for example a theory *and* a physicist. The latter is the entity with respect to which the usefulness of the former is measured. Hence, before we can hope to find semantics in a syntactic system, we need to identify these parts in it. Let us therefore assume that some part of a system corresponds to "organism", and the rest of it to it's "environment". It then becomes possible to define for instance that those things in

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the environment that influence the organism are “meaningful” to it. Or that those things under the organism’s control are “useful” to it. Such relationships are generally referred to as *closure* relationships. More advanced closure relationships are also possible, like Maturana and Varela’s autopoiesis (Maturana et al. 1980) (organizational closure), Rosen’s closure to efficient cause, Howard Pattee’s semantic closure (Pattee 1995) or Niklas Luhmann’s operational closure (Luhmann et al. 1995). Most if not all of these notions can be formalized, so there is no reason to conclude that a formal theory of meaning is impossible.

A next question we can ask is “when is a formal theory of meaning useful (to us)?” Answering this question also requires closure. This time, however, the question is how closure can be achieved for the notion of usefulness or closure itself. Recall that, in the case of Physics, a theory must apply to the physicist’s reality: it must allow him to control the outcome of physical experiments. Similarly, a useful theory of meaning must allow us, biosemioticians, to design and build actual machines with a purpose or “telos” *of their own*. One of the first people to realize this was John von Neumann who, in the last part of his life, developed a theory of self-replicating automata.

Whether von Neumann’s reasons for developing his theory were the same as ours is not clear, but at least there are a number of striking parallels. Von Neumann was very well acquainted with Turing’s work and the formalization of syntax. Moreover, he understood that the computations that Turing machines perform can be useful, provided that they receive a “proper meaning”, that is, are associated with things and processes in the physical world. Precisely this possibility explains the success of the modern computer (for which, not incidentally, von Neumann designed the original architecture—the “von Neumann architecture”).

As mentioned, von Neumann also took the next step by demanding that the computations should be useful not to the human computer user, but to the computing machine itself. This is precisely what is achieved when the computations lead to the computing machine’s physical reproduction. Thus, by eliminating the user from the picture in this way, von Neumann effectively objectivized the notion of usefulness and took an important step in the development of a scientific theory of meaning. Moreover, by keeping the rest of reality into the picture, he achieved the strongest possible form of closure, namely *material* or *physical closure*. For these reasons, von Neuman’s legacy can rightfully be described as one of the first scientific biosemiotic theories ever formulated.

Von Neumann could not include all of reality in his theory: to keep things tractable he had to move from a “physical model” to a model in terms of cellular automata. He wrote about this that “by axiomatizing automata in this manner, one has thrown half of the problem out of the window, and it may be the more important half” (von Neumann et al. 1966). Nevertheless, the foundations of von Neumann’s theory remain solid, which explains why so many of its components were also identified in living cells. His design for a self-reproducing machine, for instance, was formulated well before the discovery of DNA but nevertheless already contained a similar component, as well as mechanisms for transcription, translation and replication. Unfortunately, biology has not yet been able to appreciate von Neumann’s legacy to it’s full extent, with the exception perhaps of some researchers (Howard Pattee, for instance, stated in 2008 that “Biosemiotics distinguishes life from inanimate matter by its dependence on physical construction controlled by coded symbolic information." This is an almost literal description of von Neumann's architecture for self-reproducing automata.) At the same time, molecular biology has generated a tremendous amount of new data, and the more data becomes available, the more it becomes clear that we also need a theory of meaning and function to make sense of it. Interestingly, similar developments are taking place in other fields. Chomsky's attempt to ban semantics out of linguistics, for instance, is being challenged by an increasing number of researchers.

Given these developments in light of the legacy of such an extraordinary mind, why is it that most biologists still consider it impossible, not worthy, or often even unscientific to introduce semantics into the field? Partly, this is for historical reasons. The ancient controversy between *mechanism* and *vitalism* (or between mechanism and *mentalism* in the case of linguistics and philosophy) undoubtedly still prohibits many contemporary biologists to take this step. This has lead to a situation where, for most biologists (and many other scientists), it is acceptable to describe a man as "trying to capture a fly", but not to describe a fly as "trying to escape", because flies are not rational agents and consequently do not "try" anything. However, such a position prevents an appreciation of the fact that there nevertheless is "a unique something about the observed behavior of the fly that quite emphatically invites this anthropomorphism and which renders this behavior far better suited to such an analogy and teleological conception than, say, the behavior of a falling stone" (Sommerhof et al. 1950). In my opinion, as long as theoretical biology refuses to acknowledge this fact and dismisses all scientific inquiries into the nature of meaning and life itself, it does not, strictly speaking, deserve to be called "theoretical biology".

But another reason, I believe, might be a general ignorance and lack of appreciation for von Neumann's legacy, and in particular for what it contributes to a scientific biosemiotics. Let me therefore summarize some of it once again. Any candidate theory of meaning will have to acknowledge the following basic axioms and principles. First, it must acknowledge that semantics is not something that extends syntax, but rather is something that restricts it: it is what distinguishes meaningful from meaningless syntax. Second, semantic notions are inherently relational: they require reference to an organism in an environment and imply a relation of closure between them. Third, in order to have a useful theory of meaning, the closure relationships must ultimately map onto the physical world. Fourth, in a general theory, the closure relationships that generate meaning must be characterized in a relativistic fashion, that is, independent of the relationships in which the scientific biosemiotician takes part himself. Like in physics, the last two principles assure that it is the objective physical reality, and not the experimenter's privileged position and subjective observations, that ultimately determine the validity of the theory.

None of the above criteria resist formalization. In particular, they are met by any theory that allows us to design and build physical self-reproducing machines. This is why von Neumann's theory of self-reproducing automata really is one of the first scientific biosemiotic theories, and why I strongly recommend to take Dennis Waters' advice in his contribution to the current issue: that we should reconsider von Neumann's legacy and investigate what it might bring to our field, whether it is to understand living cells, multi-celled organisms, language and culture, or life itself.

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