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A dynamical model of the meaning of information

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Abstract

The main challenge for information science is to naturalize the semantic content of information. This can only be achieved in the context of a naturalized teleology (by 'teleology' is meant the coherence and the coordination of the physical forces which constitute the living state). Neither semiotics nor cybernetics are capable of performing this task, but non-equilibrium thermodynamics and non-linear dynamics may be. A physical theory of the meaning of information is sketched, first by identifying biofunctions with generalized non-linear oscillators and their associated phase-space attractors, and then by postulating the existence, within all such oscillators, of a component capable of coordinating low-energy interactions with the correct environmental conditions supporting the dynamical stability of the oscillator. The meaning of information is thus interpreted as the prediction of successful functional action.

Keywords: Meaning; Information; Teleology; Non-linear dynamics

1. The meaning of information is the fundamental problem of information science

Communication may be defined as the transmission across space or time of a patterned material or energy structure from a sender to a receiver, for both of whom the structure is meaningful. Shannonian information theory is a mathematical tool for studying the constraints on the transmission phase of this process, i.e. the transfer of meaningful patterns, or messages, over a channel. It tells us, roughly, that the information content of a message is inversely related to the probability of the occurrence of that particular structural configuration as measured against the set of all possible configurations of the physical structure in question. Thus, the lower the probability of a given message, the greater its capacity for bearing meaningful information.

Now this is certainly a very interesting thing to know, particularly if one is designing a communications system of some sort. Note, however, that nowhere has anything yet been said about the interpretation of the message at either end of the channel. That is, classical information theory ignores the semantic aspect of information — the problem of what it means, in physical terms, for a particular material structure to have a meaning — as Shannon himself was the first to admit (Shannon and Weaver, 1963). It simply takes for granted the existence of a sender and a receiver ('interpretants,' in semiotic parlance) standing outside the communication channel who provide the semantic link between the message ('sign') and its referent ('object'). It is the nature of this link which constitutes the problem of the meaning of

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information, and on this subject classical information theory is silent.

The dilemma facing information science is this. If the notion of information is properly restricted to its syntactic role as a measure of channel carrying capacity, then it is mathematically rigorous but boring. If, on the other hand, the concept is improperly relaxed so as to encompass the semantic content of communication, then it becomes profoundly interesting, but remains vague and mysterious. Due to systematic equivocation between these two senses of the term, the scientific respectability of the boring kind of information has been surreptitiously transferred to the exciting kind, and the concept has taken on the aura of a fundamental physical principle on a par with matter and energy. But, as Ho (1993) has remarked, 'information' is not something separate from energy and organization. The real question is: What sort of organization of energy (dynamics) is necessary in order to give rise to meaning? There are two disciplines, in particular, which make central use of the concept of information whose practitioners might claim already to have answered this question: namely, semiotics and cybernetics. The validity of these claims is briefly examined in the next section.

2. Neither semiotics nor cybernetics is the solution

Peircean semiotics takes a step beyond Shannonian information theory in that it explicitly includes the interpretant for whom a sign is meaningful within its purview. As the field has developed in recent years, it has also become more and more grounded in biology, extending the general analysis of sign use developed for human beings to other animals, to plants, and to living things generally (Sebeok and Umiker-Sebeok, 1992). This is promising, as far as it goes. It is certainly worthwhile to show that human communication is derived evolutionarily from the sign use of simpler organisms. However, semiotics does not go nearly far enough. Whether it is focusing on human beings or single cells, in the end semiotic analysis is always left with the interpretant as a primitive concept which is itself unexplained. So long as semiotics continues to treat the interpretant as a black box, it will go on begging the question of the physical basis of meaning. In order to open up the interpretant and get inside, a more fundamental approach is needed.

At first glance, cybernetics would appear to provide just the key with which to open up the black box of the interpretant that semiotics lacks. A cybernetic system is a physical system whose parts interact in such a way as to produce a particular system-state, and not some other one. This determinate configuration of parts is the 'goal-state' of the system. Likewise, as we have seen, semantic information involves the similar specification of a particular state of a system, as opposed to other physically possible but unrealized states. Therefore, it would appear that a message is a species of goal state; that is, the property of having a meaning is closely related, somehow or other, to the property of being goal-directed. In other words, the problem of the meaning of information is a subset of the problem of teleology. But if that is the case, then cybernetics would appear to be ideally suited to tackling the problem of the meaning of information, since it is often held to have solved the problem of teleology once and for all. And, to be sure, a servomechanism homing in on its goal state by means of appropriately-designed negative feedback loops would appear to be an existence proof that teleological behavior can be reduced to mechanistic causality. However, in order to assess this claim properly, let us first look a little more closely at what exactly is meant by 'the problem of teleology.'

Teleology has been one of the most vexatious concepts in the history of ideas, having assumed many different guises over the years (Lennox, 1992). If there were a core description of the problem that all could agree on, though, it might go something like this. While we assume that every individual aspect of biological organization can be explained mechanistically, nevertheless, it is difficult (or impossible) to give a convincing mechanistic explanation of the coherence and the coordination of the individual causes which collectively produce that organization. Indeed, it was in just these terms that the problem was already viewed in Antiquity. For example, in a well-known passage (De part. animal. 641^{a}5–15), Aristotle maintains that it would be just as mistaken to explain living things in terms of 'efficient causes' alone (in Greek, arche kineseos: 'source of motion'), in the manner of Democritus, as it would be to explain human artifacts in that way. With respect to organic nature in general, he finds it necessary to introduce another causative factor. This is the 'final' cause (telos: 'end') — that is, the goal toward which a process tends. For Aristotle, final causes are an indispensable part of the explanation of organized wholes, whether natural or artificial.

For us, just as surely as for Aristotle, the fundamental problem lies in the coordination and the coherence of efficient causes which conspire to produce a particular system state, and not some other one. It is this preference of one state over another, this striving for continued existence in that state, this conatus inherent in all living things that is so hard to reconcile with the rest of our scientific worldview. The question before us, therefore, is whether cybernetics is capable of effecting this reconciliation.

When the problem is stated in this way, it is immediately obvious that cybernetics alone cannot do the job. That is because, in order to explain teleology, cybernetics relies almost exclusively on the machine metaphor. However, while organisms may in some sense be cybernetic systems (i.e. physical systems that converge on a goal state), it is clear that they are not machines. The essence of the machine metaphor is the idea that a physical system can be perfectly simulated, without remainder, by a formal system of recursion rules (i.e. an algorithm). However, as Rosen (1991) has convincingly argued, the notion of a goal state cannot even be coherently articulated within such a system, that is, in terms of syntax alone. There is simply no way to specify a particular state-configuration of a mechanism as privileged — to interpret it as a goal-state — from inside the mechanism itself. In order to do that, it is necessary to step outside the system altogether. Machines possess teleological features because we have imposed them from without. Their goal-states are not intrinsic to them at all; they are only goals for us. In short, there is nothing in the closed universe of mechanistic causation which can account for the source of organization, not even in machines themselves, much less in organisms.

It is true that natural selection is often invoked at this point, as an adjunct to cybernetics; however, this is a futile move. As has recently been pointed out by a number of authors (e.g. Swenson, 1991; Goodwin, 1992; Fontana et al., 1994), natural selection presupposes biological order; therefore, it cannot itself be the primary source of that order. To see this, it is enough to consider the neo-Darwinian notion of 'fitness.' One of two things must be the case. Either fitness is interpreted as differential reproduction (what survives, survives), in which case natural selection reduces to a tautology, or else fitness is interpreted as adaptedness (what is well-designed survives), in which case natural selection begs the question of the origin of design. Either way, we are no wiser than we were before about the ultimate source of biological organization. Nor can the origin of order be explained away by invoking 'chance'; it is beyond doubt that the random (as opposed to lawlike) self-organization of a system as complex as even a nucleic acid, much less a cell, is thermodynamically impossible (Yockey, 1992).

In the end, the problem with Darwinism is that it remains wedded to the Newtonian, mechanistic worldview (Cornell, 1986). Since it is based upon the same machine metaphor as cybernetics, it has no intellectual resources that could remedy the latter's deficiencies. The whole point of both selection theory and cybernetics is to naturalize teleology; but, as Newton himself and the other 17th-century 'mechanical philosophers' were well aware, and as Rosen has recently reminded us (1991), far from representing the triumph of naturalism, the notion of the world-machine actually implies a supramundane, anthropomorphic designer! Evidently, then, a truly naturalized teleology must be sought within the framework of a 'postmechanistic' (Davies and Gribbin, 1992) science.

If our goal is to explain the coordination and the coherence which lie at the heart of the living state, then it surely makes sense to turn our attention to those areas of natural science which deal directly with coherent, collective phenomena. These include non-equilibrium thermodynamics, non-linear dynamics, and a number of related fields which have come to be referred to as the 'sciences of complexity' (see Barham 1990, 1992, 1995; Ho, 1993; Kauffman, 1993; Fontana and Buss, 1994; Yates, 1994; as well as the references therein). In the next two sections, I shall attempt to show how certain concepts derived from these disciplines can be used to throw light, first on the problem of teleology, then on that of the meaning of information.

3. Teleology in dynamical perspective

In thermodynamically-isolated systems, local energy potentials will be smoothed out as the system relaxes to equilibrium in accordance with the Second Law. In systems thermodynamically open to energy and material flows in which the flux rate is greater than the thermal relaxation time, a steady state will be established away from equilibrium so long as the flow continues. In such non-equilibrium systems, it has been shown (Morowitz, 1979; Prigogine, 1980; Matsuno, 1989; Swenson, 1992) that global, coherent cycling is the expected result, since under these conditions the spontaneous creation of macroscopic structures dissipates energy more rapidly than thermal relaxation can (hence the name 'dissipative structures'). This is the fundamental physical reason why cycles, or oscillations, are discernible in almost all functional activity (Glass and Mackey, 1988; Winfree, 1990; Lloyd and Rossi, 1992). Although all such functional cycles are embedded within densely-nested hierarchical networks of other functions, nevertheless, at any given level, each one enjoys a limited degree of coherence and autonomy. This suggests that we might model functional activity in general, at whatever hierarchical level it occurs, by means of the notion of a non-linear oscillator and its associated phase-space attractor (by which is meant the set of equifinal, or many-to-one, virtual trajectories mapping all possible initial states of the system onto its actual final state). Once we have taken this step, then the notion of the 'success' of a functional action may be identified with its continued oscillation (or, in the terminology of non-linear dynamics, the preservation of its dynamical stability).

To my knowledge, Delattre (1986) was the first person explicitly to propose this dynamical approach to the problem of teleology (or, as he says, 'finality'). However, his approach still leaves a number of problems unsolved. The most important of these is the fact that, while all biological systems exhibit equifinality, not all equifinal systems are biological; equifinality is a necessary, but by no means a sufficient condition for teleological behavior in the sense of biological functionality. Clearly, there is still a crucial piece of the puzzle missing. Fortunately, consideration of some of the basic thermodynamical properties of living things provides us with some hints as to what the missing piece might be.

One of the chief properties distinguishing biological systems from inorganic ones is their limited autonomy from local energy potentials. More precisely, it is the ability of biological oscillators to vary their rate of energy consumption independently of variations in local gradients thanks to their 'on-board' energy supply in the form of ATP. This ability allows living things to avoid slavish dependence on their surround and to resist disintegration when external conditions deteriorate by actively seeking out more favorable conditions, either in time (by slowing down their metabolism in order to conserve on-board supplies) or in space (by speeding it up in order to move about). As evidence that this is the crucial property which distinguishes a biological non-linear oscillator from a purely physical or chemical one, imagine the following: a hurricane that is able to prolong its life span, either by slowing down in order to conserve energy while waiting for improved atmospheric conditions, or else by speeding up to actively avoid land masses. Such a system would appear to us to be alive!

Note that this limited independence of living things from local energy potentials has a crucial corollary: a biological oscillator must be able to distinguish between those conditions external to itself which will support its continued oscillation, and those which will not. In other words, energy autonomy — and hence life itself — implies cognition!

4. A dynamical model of the meaning of information

How is it possible for a biofunction, conceived of as a non-linear oscillator, to acquire this ability to distinguish between those external conditions which will support its continued oscillation and those which will not, and to coordinate its functional action accordingly so that its dynamical stability will be preserved? The answer seems to be that living systems achieve limited energy autonomy from local, high-energy potentials by becoming sensitive to non-local, low-energy fluxes. As Swenson has put it (1992):

> ...whereas in non-living systems the dynamics are governed by local field potentials (with dimensions of mass, length, and time, viz, 'mass-based' fields), the dynamics of the living are governed by non-local potentials linked together through observables with dimensions of length and time (kinematic or information fields).

Thus, the chief difference between an organism and an inorganic non-linear oscillator is the organism's ability to use low-energy fluxes from a distal source in order to detect high-energy potentials before it becomes thermodynamically coupled with them. But how, in turn, is this possible?

In order to explain this seemingly mysterious ability, I have proposed (Barham, 1990) that we postulate a fundamental differentiation within all biofunctions between: (a) a high-energy interaction of the oscillator with a set of constraints in its surround (the functional action as a whole); and (b) a low-energy interaction of a subsystem of the oscillator with a second set of constraints which are highly correlated with the first set. Note that this postulated differentiation implies the existence of a component within every biofunction capable of undergoing the low-energy interaction; I have proposed that this subsystem be called the 'epistemon' (in essence, the epistemon is a generalization of the notion of a sense organ). This conjecture leads naturally to a tetradic model of perception and action, as follows (see Fig. 1).

First, we posit an existing biofunction (a) coupled to its surround in such a way that its functional action is ordinarily successful (i.e. a dynamically-stable non-linear oscillator). Next, we pick out those high-energy constraints (b) in the surround with which (a) ordinarily interacts. Then, we identify a second set of environmental constraints (c) which are highly correlated with the first set, but which are lower in energy. Finally, we

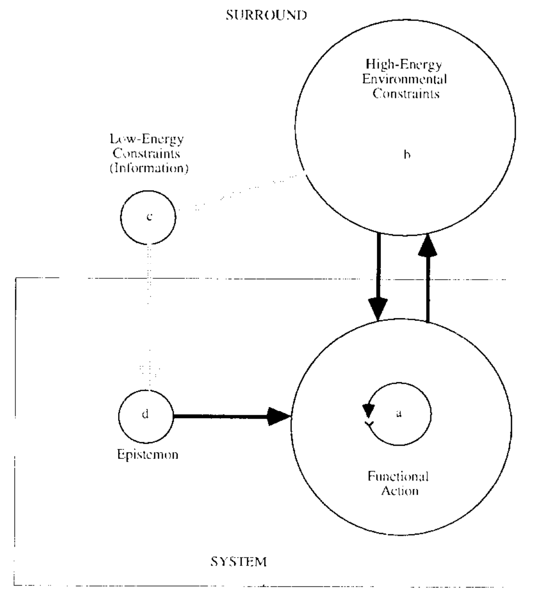

Fig. 1. A biological function modeled as a non-linear oscillator with a low-energy trigger. (See text for details.)

have the postulated universal subsystem (d) (the epistemon) which is capable of interacting with these low-energy constraints. As a result of the interaction between the low-energy constraints and the epistemon, the latter undergoes a state transition which acts as a trigger for the functional action (a), thus completing one perception-action cycle. Now, provided only that the two sets of exogenous constraints — high-energy (b) and low-energy (c) — stand in some causal relation to each other (the precise nature of which will vary from case to case), then the correlation (d)–(a) between the epistemon state transition and the oscillation of the biofunction becomes, in effect, an internal projection of the correlation (b)–(c) between the high- and low-energy constraints. That is, the low-energy constraints act as semantic information with respect to the functional action, indicating the presence of those external conditions which successfully support its action.

Another way of putting it is to say that the interaction between the low-energy (or informational) constraints and the epistemon predicts that the overall functional action, if undertaken now, will be successful. In short, the meaning of information is the prediction of the success of functional action.

5. Conclusion

What sort of empirical support does this model enjoy? In the first place, it would appear that a great many biofunctions at all hierarchical levels do in fact embody the tetradic structure. For example, at the low end of the scale, enzymes make use of a non-covalent interaction with their substrates in order to trigger a conformational change in the enzyme-substrate complex, which in turn leads to the making or breaking of covalent bonds (in this case, the epistemon is the enzyme's active site). At the other end of the spectrum, the coherent, self-organizing activity of nerve cell assemblies in the brain, which can be detected in the form of chaotic attractors in EEG data (Freeman, 1995; Kelso, 1995), are the epistemons which interact with ambient low-energy electromagnetic radiation (light) and acoustic vibrations (sound) in order to coordinate the successful navigation of our high-mass bodies through space.

From a theoretical perspective, the model is particularly attractive in that it contains no homunculus or other illicit anthropomorphic elements. As such, it demystifies the notion of semantic content and places it on a firm physical foundation. Furthermore, it helps to wean us from the representationalist viewpoint of traditional cognitive science by allowing the lawlike correlations between the strong and weak interactions to play the role of representations. From the dynamical perspective, the brain doesn't represent the environment; rather, it establishes predictive correlations between its own epistemons (chaotic attractors) and external structures. Thus, the brain and the body together interact intelligently with the world, not through a computer-like simulation — which would lead to a homuncular infinite regress — but rather by conforming to natural law (in the form of satisficing constraints) like any other physical process (van Gelder, 1995).

The dynamical approach also dovetails nicely with other contemporary efforts to move beyond representationalism in cognitive science. I am thinking, especially, of certain trends within Gibsonian 'ecological psychology' (e.g. Swenson and Turvey, 1991) and the 'autonomous situated agents' school of robotics pioneered by Rodney Brooks (1995).

Finally, perhaps the greatest strength of the present model is just its grounding in non-linear dynamics. For, any model of the meaning of information must be teleological; the only question is whether the teleology will be openly acknowledged or swept under the rug, and, if acknowledged, how it will be naturalized. Non-equilibrium thermodynamics and non-linear dynamics are the logical candidates for naturalizing teleology, and therefore provide the most promising foundation upon which to build a future information science.

References

Barham, J., 1990, A Poincaréan approach to evolutionary epistemology. J. Soc. Biol. Struct. 13, 193–258.

Barham, J., 1992, From enzymes to $E = mc^2$: A reply to critics. J. Soc. Evol. Sys. (continues J. Soc. Biol. Struct.) 15, 249–305.

Barham, J., 1995, Ni Darwin, ni Derrida. J. Soc. Evol. Sys. 18, 277–308.

Brooks, R.A., 1995, Intelligence without reason, in: The Artificial Life Route to Artificial Intelligence, L. Steels and R. Brooks (eds.) (Lawrence Erlbaum Associates, Hillsdale, NJ) pp. 25–81.

Cornell, J.F., 1986, Newton of the grassblade? Darwin and the problem of organic teleology. Isis 77, 405–421.

Davies, P. and Gribbin, J., 1992, The Matter Myth (Touchstone Books/Simon & Schuster, New York).

Delattre, P., 1986, An approach to the notion of finality according to the concepts of qualitative dynamics, in: Dynamical Systems: A Renewal of Mechanism, S. Diner, D. Fargue and G. Lochak (eds.) (World Scientific, Singapore) pp. 149–154.

Fontana, W. and Buss, L.W., 1994, 'The arrival of the fittest': Towards a theory of biological organization. Bull. Math. Biol. 56, 1–64.

Fontana, W., Wagner, G. and Buss, L.W., 1994, Beyond digital naturalism. Artificial life 1, 211–227. Reprinted in: Artificial Life: An Overview, C.G. Langton (ed.) (Bradford Books/MIT Press, Cambridge, MA, 1995) pp. 211–227.

Freeman, W.J., 1995, Societies of Brains (Lawrence Erlbaum Associates, Hillsdale, NJ).

Glass, L. and Mackey, M.C., 1988, From Clocks to Chaos: The Rhythms of Life (Princeton University Press, Princeton).

Goodwin, B.C., 1992, Evolution and the generative order, in: Theoretical Biology: Epigenetic and Evolutionary Order from Complex Systems, B. Goodwin and P. Saunders (eds.) (Johns Hopkins University Press, Baltimore) pp. 89–100. (Originally published by Edinburgh University Press, Edinburgh, in 1989.)

Ho, M.-W., 1993, The Rainbow and the Worm: The Physics of Organisms (World Scientific, Singapore).

Kauffman, S.A., 1993, The Origins of Order: Self-Organization and Selection in Evolution (Oxford University Press, New York).

Kelso, J.A.S., 1995, Dynamic Patterns: The Self-Organization of Brain and Behavior (Bradford Books/MIT Press, Cambridge, MA).

Lennox, J.G., 1992, Teleology, in: Keywords in Evolutionary Biology, E.F. Keller and E.A. Lloyd (eds.) (Harvard University Press, Cambridge, MA) pp. 324–333.

Lloyd, D. and Rossi, E.L. (eds.), 1992, Ultradian Rhythms in Life Processes (Springer-Verlag, London).

Matsuno, K., 1989, Protobiology: Physical Basis of Biology (CRC Press, Boca Raton, FL).

Morowitz, H.J., 1979, Energy Flow in Biology (Ox Bow Press, Woodbridge, CT). (Originally published by Academic Press, New York, in 1968.)

Prigogine, I., 1980, From Being to Becoming (W.H. Freeman and Company, San Francisco).

Rosen, R., 1991, Life Itself (Columbia University Press, New York).

Sebeok, T.A. and Umiker-Sebeok, J. (eds.), 1992, Biosemiotics: The Semiotic Web 1991 (Mouton de Gruyter, Berlin).

Shannon, C.E. and Weaver, W., 1963, The Mathematical Theory of Communication (University of Illinois Press, Urbana, IL). (Originally published in 1949.)

Swenson, R., 1991, End-directed physics and evolutionary ordering: obviating the problem of the population of one, in: The Cybernetics of Complex Systems, F. Geyer (ed.) (Inter-Systems Publications, Salinas, CA) pp. 41–60.

Swenson, R., 1992, Order, evolution, and natural law: fundamental relations in complex system theory, in: Cybernetics and Applied Systems, C.V. Negoita (ed.) (Marcel Dekker, New York) pp. 125–148.

Swenson, R. and Turvey, M.T., 1991, Thermodynamic reasons for perception-action cycles. Ecol. Psychol. 3, 317–348.

van Gelder, T., 1995, What might cognition be, if not computation? J. Philos. 91, 345–381.

Winfree, A.T., 1990, The Geometry of Biological Time. Corrected reprint (Springer-Verlag, Berlin). (Originally published in 1980.)

Yates, F.E., 1994, Order and complexity in dynamical systems: homeodynamics as a generalized mechanics for biology. Math. Comput. Modelling 19, 49–74.

Yockey, H.P., 1992, Information Theory and Molecular Biology (Cambridge University Press, Cambridge).