CONTROL INFORMATION:

THE MISSING ELEMENT IN NORBERT WIENER'S CYBERNETIC PARADIGM?

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ABSTRACT

Norbert Wiener's cybernetic paradigm represents one of the seminal ideas of the 20th century. It has provided a general framework for analyzing communications and control processes in purposeful systems, from genomes to empires. Especially notable are the many important applications in control engineering. Nevertheless, its full potential has yet to be realized. For instance, cybernetics is relatively little used as an analytical tool in the social sciences. One reason, it is argued here, is that Wiener's framework lacks a crucial element -- a functional definition of information. The functional (content and meaning) role of information in cybernetic processes cannot be directly measured with Claude Shannon's statistical approach, which Wiener also adopted. Although so-called Shannon information has made many valuable contributions and has many important uses, it is blind to the functional properties of information. Here a radically different approach to information theory is described. After briefly critiquing the literature in information theory, a new kind of cybernetic information will be proposed which we call "control information." Control information is not a "thing" but an attribute of the relationships between things. It is defined as: ***the capacity (know how) to control the acquisition, disposition and utilization of matter/energy in purposive (cybernetic) processes****. We will briefly elucidate the concept, and we will propose a formalization in terms of a common unit of measurement, namely the quantity of "available energy" that can be controlled by a given unit of information in a given context. However, other metrics are also feasible, from money to allocations of human labor. Some illustrations will be provided and we will also briefly discuss some of the implications.*

INTRODUCTION

Norbert Wiener's *Cybernetics: Or Control and Communication in the Animal and the Machine* (1948), can truly be called one of the seminal scientific contributions of the 20th Century. Thanks to Wiener's inspired vision, cybernetic control processes are now routinely described and analyzed at virtually every level of living systems, inclusive of social, political and technological systems.[1] Cybernetic processes, including especially feedback processes, are observable in morphogenesis (the translation of genetic instructions into a mature organism), in cellular activity, in plants (see Gilroy and Trewavas 2001), in the workings of multicellular organisms with differentiated organ systems, in the behavioral dynamics of socially-organized species (such as *Apis mellifera*, the true honey bee), in the operation of household thermostats, in robotics, in aerospace engineering, and much more. Cybernetics has given us a framework for understanding one of the most fundamental aspects of living systems -- their dynamic "purposiveness", or goal-directedness. Much productive research has flowed from this paradigm, in fields as disparate as control engineering, molecular biology, plant physiology, neurobiology, psychology and economics.

And yet, cybernetics is still far from realizing its full potential. For instance, it has been relatively little-utilized in the social sciences, despite the efforts of such theorists as Karl Deutsch (1963), David Easton (1965), William Powers (1973), James Grier Miller (1978) and the present author (1983), among others. One reason for this shortfall, we believe, is that an important element is missing from Wiener's paradigm, and this omission has diminished its utility as an analytical tool.

Actually, Wiener's oversight involved more than an omission. To be precise, Wiener pointed his followers down a false trail, and this has had unfortunate consequences over the years, not only for the development of cybernetics but also for the related fields of semiotics and information theory. The problem, in essence, has to do with how information is defined and measured. Wiener failed to develop a functional definition of information, which is essential to an understanding of the role and dynamics of "communication and control" in cybernetic systems. Instead, he adopted an engineering approach which was similar to that of his colleague Claude Shannon, the "father" of information theory.[2]

INFORMATION THEORY

In his classic 1948 article and his 1949 book with Warren Weaver, Shannon confined his formulation of "communications theory" (as he initially called it) to the problem of measuring uncertainty/predictability in the transmission of "messages" between a sender and a receiver. As Shannon and his co-author wrote: "The fundamental problem of communication is that of reproducing at one point either exactly or approximately the message selected at another point. Frequently the messages have *meaning*...[But] these semantic aspects of communication are irrelevant to the engineering problem" (p. 3).

Accordingly, in Shannon's usage information refers to the capacity to reduce statistical uncertainty. If one were to utilize the binary bit as a unit of measurement, the degree of informational uncertainty would be a function of the number of bits required to eliminate it. Shannon also adopted the thermodynamics term "entropy" (at the suggestion of mathematician John von Neumann) to characterize the degree of statistical uncertainty in a given communications context before the fact. More formally, Shannon's information can be represented by the equation:

$$\mathbf{I_x = \log_2 1/P_x} \qquad \mathbf{(1)}$$

where the information content **I** of an event **x** in bits is the logarithm to the base 2 of the reciprocal of its probability. Shannon's expression for entropy, then, was:

$$\mathbf{H = K\, P_i \log_2 P_i} \qquad \mathbf{(2)}$$

where **K** refers to Ludwig Boltzmann's famous constant (1.38 X 10^{-16} erg/^{o}C) and $\mathbf{P_i}$ refers to the number of equiprobable states.

The justification for calling this quantity "entropy" came from its similarity to Boltzmann's and Willard Gibbs' statistical equations for thermodynamic entropy. However, this conflation of terms and meanings served only to exacerbate an already serious muddle. The problem first arose when physicists -- notably including Erwin Schrödinger in his legendary book, *What is Life* (1945) -- began to blur the distinction between thermodynamic (energetic) entropy (or its converse, which Schrödinger called "negative entropy") and physical (structural) order/disorder. The former usage refers to the availability of energy to do work, whereas the latter usage may be quite unrelated to any work potential. (More on this matter below.) Shannon was careful to differentiate between informational entropy and thermodynamic entropy, but other information theorists have not been so punctilious. Some of Shannon's followers have even suggested that there is an isomorphy, or equivalence, between statistical, energetic and physical order/disorder. However, this is not correct.

One consequence of this conceptual and theoretical conflation was that Shannon's form of information came to be viewed by many theorists as having more potency as an instrumentality for creating order/organization in the natural world than any purely statistical measure can properly support. It imputes causal efficacy to the statistical properties of the "messages" themselves without regard to their content. Unfortunately, Wiener followed the same approach.

In his landmark book, published in the same year that Shannon's classic article appeared, Wiener did discuss the functional aspect of information in various places (e.g., Chapter VII on "Information, Language and Society"), but his formal definition and mathematical treatment involved what he called "a statistical theory of the amount of information" (p. 10). Thus, "the transmission of information is impossible save as a transmission of alternatives....Just as the amount of information in a system is a measure of its degree of organization, so the entropy of a system is a measure of its disorganization" (pp. 10,11). Later on Wiener described enzymes, animals and other cybernetic processes as "metastable Maxwell's Demons, decreasing entropy....Information represents a negative entropy" (p. 58).[4] (In fact, Wiener did not provide an explicit formalization in his long, discursive, and mathematically challenging chapter on the subject; instead, he focussed on how to measure the "amount" of information.)

The suggestion that information is somehow equivalent to negative entropy (i.e., Schrödinger's neologism for available energy, or statistical/structural order, depending upon which version of the term entropy is being referenced) has also encouraged a tendency to reify the concept of information. Biologist Tom Stonier (1990) is perhaps the most emphatic proponent of this view. He argues that information is "real". He writes: "*Information exists.* It does not need to be *perceived* to exist. It requires no intelligence to interpret it. It does not have to have *meaning* to exist. It exists [his emphasis]" (p. 21). It is an embedded property of all physical order, he says.

What we refer to as "statistical" and "structural" (i.e., order-related) formulations of information theory have made many important contributions to communications technology, computer science and related fields. However, these approaches cannot lead to a "unifying theory" of information for the simple reason that they are blind to the functional (teleonomic) basis of information in living (and human) systems, as Shannon acknowledged. Indeed, objections to various overclaims for information theory began almost immediately after Shannon published his path-breaking formulation. As early as 1956, Anatol Rapoport published an important rebuttal article entitled "The Promise and Pitfalls of Information Theory." Rapoport noted that "it is misleading in a crucial way to view <information' as something that can be poured into an empty vessel, like a fluid or even energy." In what might in retrospect be considered a major understatement, Rapoport commented that "the transition from the concept of information in the technical (communication engineering sense) to the semantic (theory of meaning) sense" will be "difficult."

In a similar vein, Heinz von Foerster (1966, 1980, inter alia) stressed the functional importance of information for living systems. The nonsense sentences "Socrates is identical" or "4+4 = purple" differ profoundly from sentences that have meaning. Likewise, the aggregate number of light photons that might be processed by the retina of a human eye are less relevant from a functional point of view than the analytical and interpretative processes that go on in the brain (the uses that are made of those photons). As von Foerster noted, "Information' is a relational concept that assumes meaning only when related to the cognitive structure of the observer."

MacKay (1968[1961]) also pointed out that Shannon's information, and similar formulations, are crucially dependent upon the existence of a sender and a receiver; otherwise, one is only describing a physical process -- a flow of electrons, photons, and the like. For instance, a television screen may display 10^7 bits of statistical information per second. If one were to transmit an entirely new pattern once each second, the number of bits involved (the "amount" of information) would soon become astronomical, but it would have absolutely no meaning to a viewer. (Similar arguments can be found in Ackoff 1957-58; von Bertalanffy 1968; Bateson 1972, 1979; Cherry 1978; Krippendorff 1979; Maturana and Varela 1980; Eco 1986; Brier 1992; and Qvortrup 1993, among many others).

Nevertheless, the literature associated with "statistical" and "structural" information theory has continued to grow over the years, while the problem of "meaning" and, more broadly, the functional aspect of information has been ignored, skirted, or acknowledged but largely passed over by the workers in information theory, with some recent exceptions. Other theorists have finessed the problem by working within the framework of a particular information coding system, whether it be DNA codons or phonemes. Yet the fundamental problem remains unresolved. If information is said by some to do work, how can it be differentiated from energy? If information is equated with thermodynamic order, how does it differ from available energy, or physical order (depending upon which version of the term is being referenced)?

But more important, from a functional perspective information is not equivalent either to thermodynamic entropy or "negative entropy" (order). If it were, why confuse matters by using different terms for the same thing? In fact, this conflation of different phenomena involves a fundamental dimensional error. Information (properly defined) has no dimensions, while thermodynamic entropy has the dimensions of energy divided by temperature. It is comparable to equating voltage with length, or mass with velocity. Indeed, physicist Rolf Landauer (1996) has devised a thought experiment which illustrates his argument that there is no minimum energy expenditure that is necessarily associated with information flows; in theory, the information flow could be made "reversible" (see also Bennett 1988).

Also, information (unlike energy) can be endlessly reused; there is no law of informational entropy. Nor is information "conserved"; it can be multiplied indefinitely. It has also been observed that, in some communications systems, information may flow in the opposite direction from the energy flow (for example, the old-fashioned Morse Code telegraph). Also, highly organized biological systems tend to be relatively more efficient users of energy; they use information to economize on energy consumption and, in so doing, validate the distinctions between information, energy and biological organization.

A further objection is that information by itself cannot do anything; it cannot control a thermodynamic process without the presence of a "user" that can do purposeful work. In other words, information must be distinguished functionally from the process of exercising control, yet many theorists simply take this operation for granted, as F. Clerk Maxwell did with his "demon" (and as many other physicists have done since). It is this overlooked aspect -- this "free ride" -- that has allowed physical scientists to theorize about informational processes without acknowledging the necessary role of cybernetic control processes. Indeed, cybernetic processes cannot even be described by the laws of physics (see Corning and Kline 1998a).

Another theoretical problem with traditional information theory concerns the contexts in which information does not have a statistical aspect. This can be illustrated by embellishing an example used by Wicken (1987) to show how Shannon information depends upon the existence of alternatives. Flipping a coin repeatedly is said to produce information -- a unique sequence among many possible alternatives. But if the coin is two-headed, the outcome of each flip is pre-determined, and so no statistical information is generated. Now suppose that there are two bettors, one of whom does not know that the coin is two-headed (at least initially). Consequently, some money might change hands, even though no statistical information is produced. Furthermore, after a few flips of the coin the "sucker" might get suspicious and challenge the process, precisely because of the absence of statistical properties. Clearly, some other kind of information -- what we call "control information" -- was also involved in this situation.

Defining information as a manifestation, or embedded property of physical order (e.g., Tribus, Riedl, Brooks and Wiley, Stonier, Wicken and others) presents similar difficulties. First, there is the problem of defining order in any empirically-consistent, measurable way. We do not gain anything by conflating certain properties of the physical-biological world with a concept that has an inescapably functional connotation for living systems. To the contrary, we obscure the many properties of information which cannot be associated with physical order per se, such as the feedback in cybernetic processes that can even produce disordering effects. (Feedback is highly sensitive to phase relationships in periodic systems; in a poorly "tuned" system, feedback can produce all manner of destructive consequences.)[5]

In fact, whole categories of information in living systems are excluded altogether by equating information with order. For many organisms, physical phenomena of various kinds (gravity, the earth's magnetic field, thermal or chemical gradients, moisture, even the ambient flow of solar photons) provide useful "information". Living organisms are constantly sensing, filtering, storing and deleting "data" on a real-time basis, but only some of it is used. This information is not so much "ordered" as "sensed" or "detected" and then utilized in purposeful ways -- only a portion of which can be said to be order-creating. One example is the role of facial expressions in shaping the interactions among humans (and other animals), as Paul Ekman (1973, 1982) has demonstrated, following Darwin's lead in *The Expression of the Emotions in Man and Animals* (1965[1873]). Facial expressions, with or without "intent", can convey important information, but only to another animal that can properly interpret their meaning.

But perhaps most important, definitions of information that equate physical/statistical order with functional organization commit a fundamental typological error. Biological organization has properties that are not reducible to physical order. (On this point, see Corning and Kline 1998a.) In fact, cybernetic processes have the perverse property of being relational in nature -- they are always dependent upon the relationship between a given system (inclusive of its goals) and its specific environment.

CONTROL INFORMATION

Accordingly, we propose that a categorical distinction should be made between what we have called "statistical" and "structural" definitions of information (which have their uses) and "control information" -- which we will designate "I_C", and which we will attempt to formalize below. We define control information as: **the capacity (know how) to control the acquisition, disposition and utilization of matter/energy in purposive (teleonomic) processes**.

Control information has a number of distinctive properties. First and foremost, it does not have any independent existence. It is not a concrete "thing", or a mechanism. It is defined (and specified) by the relationship between a particular cybernetic system (a "user") and its environment(s). In this paradigm, the physical environment "contains" latent or potential control information, but this potential does not differ in any way from the physical properties of the environment and, moreover, this potential is only actualized when a purposeful system makes use of it. In other words, the very existence and functional effects produced by control information are always context-dependent and user-specific. A few examples may help to clarify this seemingly paradoxical, even counter-intuitive notion:

First, imagine a traffic intersection with a stoplight that has just turned red. The "information" conveyed by the photons of light that are emitted by the stoplight and the behavioral consequences that ensue will depend completely upon the circumstances. A motorist who does not see the light may drive right through it. Another motorist, in a hurry late at night, might observe the light and then deliberately decide to ignore it. However, to the inhabitant of a remote, hunter-gatherer society -- say a Yanomamö tribesman -- the red stoplight may represent only a puzzling apparition, while it may only be a bright colored light to an infant. Thus, the user and the informational "source" together determine the informational value and the degree of behavioral control that results.

In the second example, imagine that a large boulder straddles a hiking trail in a mountainous area. The physical properties of the boulder are invariant, but the information "extracted" by four different hikers, and the functional consequences, may vary considerably. One hiker may see the boulder merely as an obstacle and will take action to walk around it. A second one, very tired, may see it as a place to sit down and rest. A third hiker may recognize it as the landmark for a diverging trail that he was instructed to take. Now imagine a fourth hiker who is a gold prospector. Observing a small vein of gold, he proceeds to demolish the boulder to remove the gold and, in the process, destroys forever the boulder's informational potential. Again, the informational process involves an "interaction" -- a specific system-environment relationship.

A final example involves the properties of language. Linguists have long insisted that the functional properties of language (or meaning) cannot be reduced to an invariant, quantitative unit, like a binary bit. Thus, the letters in "RAT" "TAR" "ART" and "TRA" have energetic and statistical properties that are equivalent. Yet the meaning (if any) depends on the configuration -- the "gestalt". Moreover, for a small child or an adult who does not know English, none of the words have any meaning at all. In fact, written language involves an essentially arbitrary relationship between configurations of two-dimensional physical patterns and the associations that are produced, if any, in the specific reader's mind. This explains why the same configuration of letters can have very different meanings in different languages. An example is the word "gift". In English it means a present; in German it means poison.

The key point here is that "control information" causes purposeful work to be done in or by cybernetic systems. If energy, in accordance with the classical definition, is "the capacity to do work," control information is "the capacity to control the capacity to do work." Virtually everything in the universe might, potentially, have informational value (i.e., be used by cybernetic systems for some purpose), but control information is not located in the physical objects alone. It is defined by the precise relationship between a given object and a given observer/user. Indeed, biological "systems" vary tremendously in their ability even to detect different aspects of the external world. Thus, the pheromone "signals" that control the behavior of army ants will go unnoticed and ignored by humans. Elephants can detect vary low sound frequencies and dogs can detect very high frequencies that humans cannot even "hear". And hawks have some eight times the number of photoreceptors per millimeter of retina as do humans; there is a definite physical basis for the old expression about being "hawk-eyed."

As the foregoing indicates, control information has a number of distinctive properties. First, control information is always relational and context-dependent and has no independent material existence; it cannot be identified or measured independently of a specific cybernetic process. However, it can be measured (see below). Moreover, there may or may not be a "sender", or a formal communications channel, or a "message" for that matter, but there must always be a "user" -- a living system or a human-designed system. For instance, if you disassemble an automobile into its 15,000 or so component parts, it will no longer be able to utilize "instructions" from a driver.

Second, control information does not exist until it is actually used. An unread book, an "unread" genome, or an undetected pheromone represent only "potential" or "latent" information. Accordingly, the various mechanisms which exist in nature and human societies for coding, storing and transmitting potential information are reducible to their underlying physical processes; their informational properties arise only from the variety of ways in which these physical media may actually be utilized for informational purposes. To be sure, one can always make estimates or predictions about it, but control information cannot actually be measured except *in vivo* and *in situ*.

Accordingly, control information has no fixed structure or value. It is not equivalent to any specific quantity of energy, or order, or entropy, or the like. To illustrate, a single binary bit may (in theory) control an energy flow as small as a single electron or as vast as a the "signal" for a nuclear war; its power can vary tremendously, depending upon the context. (Another way of stating it is that all bits are not created equal.) Control information is analogous to money, whose value is not intrinsic but is defined in terms of specific transactions.

"Potential" control information is very often "embodied" in various information-storage and transmission media -- from DNA "templates" to the sound patterns in spoken language -- but the vehicle must not be confused with its driver. Control information is equally prevalent in the "state" properties of physical objects -- temperature, mass, velocity, viscosity, etc. There is no fundamental physical distinction between the two types of information; there is only a functional distinction.

Very often control information has synergistic properties; it emerges from an "ensemble" of informational "components" or "fragments" that may be combined in many different ways. Language provides an obvious example. A change in the arrangement of an identical set of letters converts the declaration "I shall go" into the question "shall I go?" Similar informational synergies are commonplace also with physical phenomena. Thus, the sight of a swarm of bees coming at you conveys an aggregate informational effect that is lacking if only a single bee is doing so.

By the same token, much of the information used by (and within) organisms involves processes that might be characterized as "inferential" -- that is, they derive from "the weight of the evidence" rather than from a deterministic "message". To illustrate: you may hear a fire alarm; you smell smoke; you see people running out of your building; you assess the context and your experiential "data base" and may infer that there is a fire and that it would be advisable to vacate the building. In a similar vein, it could be said that the testimony presented at a trial consists of informational "components" but only the verdict represents control information (i.e., produces definitive action).

Lies, myths, "misinformation" or "disinformation" of various kinds may also serve as "control information" insofar as they affect a user's behavior. It is not the veracity which counts in the control information paradigm but the functional effects that are produced. (Recall the two-headed coin example above.) There is, in fact, a large literature in biology on the evolution and use of "deception" as a strategy for achieving various functional outcomes.

FORMALIZING CONTROL INFORMATION

The term "control information" may be novel, but the concept itself is not idiosyncratic or alien. Many other theorists over the years have articulated similar ideas. To cite a few examples: Raymond (1950) pointed out that information controls the expenditure of energy. Rapoport (1956) characterized information as a means for resisting the Second Law and reducing entropy. MacKay (1968[1961]) noted that information "does logical work" -- it has "an organizing function" (well, some of the time at least). Biologist Paul Weiss (1971) insisted that information and biological functions are inseparable. Wicken (1987) differentiates between statistical information and what he calls "functional information," which he associates with the creation of biological "structures." Similarly, Küppers (1990), following Manfred Eigen, takes the argument to the level of nucleic acids and the very origins of life and speaks of the functional role of template-based information in creating living structures.

The problem, of course, is how to convert this perspective into an analytical framework. Specifically, the question is, how can you measure something that does not exist as a concrete physical entity? Our proposal, in essence, is that it can be measured in relation to what it does -- in relation to its "power" to control and utilize available energy and matter in or by a purposeful system. One can measure its "qualitative" effects, or its "meaning" in terms of the results that are produced -- the cybernetic "work" that is accomplished. Potentially, there are many different ways of measuring these results. However, we have chosen to confine our measuring-rod (initially) to the "thermoeconomic" realm -- that is, the capacity to control purposeful "work". Accordingly, our basic formalization utilizes available energy. Our definition is as follows:

$$\mathbf{I_C f = \ln A_u - \ln A_i} \qquad \mathbf{(3)}$$

where $\mathbf{A}$ = available energy as defined by Keenan (1941, 1951), or the energy available to do work net of the entropy of a system and its surroundings, namely,

$$\mathbf{A = E + P_o V - T_o S_C} \qquad \mathbf{(4)}$$

where $\mathbf{E}$ is the total stored energy, $\mathbf{V}$ is the volume, $\mathbf{S_C}$ is the (Clausius) entropy of the system, $\mathbf{P_o}$ is the pressure and $\mathbf{T_o}$ the absolute temperature of the surroundings. Accordingly, in our formalization, $\mathbf{A_u}$ = the total quantity of available energy potentially accessible for cybernetic control in a given situation by a given cybernetic system, $\mathbf{A_i}$ = the total available energy cost associated with bringing the available energy under control and exercising control over its use, inclusive of the cost of reducing/eliminating Shannon entropy ($\mathbf{S_S}$) or the cost of Shannon information ($\mathbf{I_S}$), and $\mathbf{f}$ represents a multiplier for the quantity of a given type of informational unit that may be present in a given context. Use of the **ln** form allows one to handle a large range of numbers while expressing both the magnitude and efficacy (or "power") of a given unit or ensemble of information. Also, if we take the exponential we get the amplification ratio, a measure of the relative "efficiency" of a given informational unit/ensemble. Thus,

$$\mathbf{\exp I_C f = [A_u/A_i]} \tag{5}$$

This formalization, it should be noted, deals only in the currency of energy. Yet cybernetic processes utilize many different kinds of currencies -- from electron flows to biochemical interactions, animal and human behavior, manufacturing processes, even monetary transactions. We believe that the utility of our formalization can be broadened by making appropriate conversions from these units into energetic equivalencies -- a well-established technique in energetic analyses dating back to various efforts to develop energy theories of economic value in the 1930s. Here we propose instead to use energetic equivalencies as a common currency for measuring control information. A similar approach can be found in the efforts of Howard Odum (1988) to develop an energetic measuring-rod for the "cost" of various kinds of embodied information in human societies. Odum uses specifically an energy-scaling factor (solar emjoules per joule) of energy inputs, which he calls "emergy." However, we use the more conventional available energy measure, and we focus instead on the "benefits" (or outputs) produced by information.

SOME ILLUSTRATIONS

We can illustrate this formulation by revisiting the examples provided above. In the red stoplight example, the signal produces a clearly observable change in the behavior of any motorist who responds by stopping, and this can readily be converted to a quantity of purposeful work output. (A proper accounting should also include the "work" of the automobile.) But what about the motorist who "runs" the stoplight? Here the analysis becomes more subtle and difficult. The potential information very likely would result in a change in the driver's degree of alertness, heart rate, blood pressure, etc., and may also result in a slowing down, speeding up, or both, of the automobile. The energetic consequences would be much smaller, but they would still be significant; the "information" would exercise some influence over the behavior of the driver (and the car). Conversely, in accordance with our definition no control information would exist for the motorist who did not see the light, or for the Yanomamö tribesman, or the infant, and there would be no measurable energetic consequences.

Similar energetic analyses could be done for the hiker example. In each of the four hypothetical cases described above, the boulder generated different quantities of control information by virtue of its influence on the behavior of each hiker. Likewise, in the language example, it is axiomatic that words have the "power" to influence human behavior. A time-honored example is the proscription against shouting "fire" in a crowded theater. This venerable legal dictum illustrates both the potential power and the context-dependent nature of control information. Indeed, advertisers and their agencies spend untold billions of dollars/pounds each year trying to find just the "right" words.

Let us also consider a comparative example -- operating an automobile versus pedaling a bicycle. The costs in monetary terms for operating a given automobile in a given setting are already quite well known and could be converted to energetic equivalents. However, we must be careful to separate the costs associated with actually performing the "work" from the control costs for the process. From this perspective, the control information costs **(A_i)** turn out to be relatively low compared with the work that an automobile can perform **(A_u)**. To simplify the analysis, the control information cost **(A_i)** could be equated with the labor (time/energy) consumed by the controller -- the driver. So, the quantity (power) of the control information associated with driving a car could be calculated in terms of the available energy consumed by the car in doing work, minus the labor cost for the operator **($A_u - A_i$)**. Now compare this with pedalling a bicycle. The control costs **(A_i)** are approximately the same, while the available energy that can be controlled **(A_u)** is reduced to the muscle work performed by the rider/controller in propelling the bike. Obviously, driving a car greatly amplifies the power of a given quantity of neuronal activity (control information).

The economic aspect of our approach should also be mentioned. As noted above, our basic equation for control information is designed to measure not the total available energy involved in a particular context but the "profits", net of the entropy and the informational costs associated with the exercise of control. This approach, we maintain, brings our equation out of the realm of theory and locates it in the real-world of economic analyses, where the relationship between costs and benefits plays an important, even decisive, role in determining whether or not potential information becomes actualized. If the efficiency (benefit-cost ratio) is very low, the likelihood that a given form of information may actually be utilized to exercise control will be reduced commensurately. It is likely to remain in the realm of "latency." Indeed, our equation (5) above expresses precisely the reason why we will never see a real-world Maxwell's demon, even if it were technically feasible. There is no way that we know of for the demon to achieve an energetic "profit". Maxwell's demon has unwittingly identified a law-like principle of control information theory; if the energetic costs of a particular type of control information exceeds the potential energetic "returns", there will be selection against its emergence and perpetuation.

What about the relationship between control information and "organization" (biological "structures")? Many theorists have pointed to the key role of information in building and maintaining biological systems. It is also a truism that much biological information is "encoded", stored and transmitted in various ways. Indeed, information is an integral part of all biological processes. To some theorists, therefore, it has seemed logical to seek a concrete informational "measuring-rod" for biological organization. We believe that no such structural measuring-rod will be found. We believe that is it is important to maintain a clear distinction between the properties of the various physical media that may serve informational purposes and their precise functional dynamics. By insisting that structural information, like any other kind, is "latent" (like an unread book) and of no direct functional significance until it is actually used in some way, we do not then have to explain such paradoxes as the fact a significant portion of the DNA in the genome of any given species may not code for anything -- i.e., may not have any informational value. (The question of why so much "junk" DNA exists is another matter.) In our scheme, latent structural information becomes control information if and when it is utilized, and its "power" is a function of its organizing ability -- the organizing "work" that it can do with the available energy at hand in relation to a given system.

It should also be noted that we have made no provision in our paradigm for developmental or "capital" costs -- say the energetic investment in designing and building a demon, or an automobile. Aside from the formidable analytical challenges, and the problem of infinite regress (how far back do you go with the bookkeeping process?), this would be likely to produce some highly skewed results. A more logical approach is to follow the lead of economists and accountants, who utilize various cost-allocation and amortization procedures to apportion the developmental costs for various economic processes. Thus, in our automobile-versus-bicycle example above, the (external) information costs associated with learning to drive or ride a bicycle, as well as the cost of providing traffic control systems (stoplights, road-signs, etc.), if allocated over the number of uses and users, might add a very small increment to the total information costs.

CONTROL INFORMATION AND SEMIOTICS

To anyone who is familiar with the large and productive field of semiotics (the doctrine of "signs"), the concept of control information may seem to be quite similar. In fact, these two formulations are convergent but have different purposes and foci. As articulated by Thomas A. Sebeok (1986), one of the leading figures in modern semiotics, the doctrine of "signs" and their meanings traces its roots to ancient Greece (see also Nöth 1990). Indeed, it has been an important theme in the entire tradition of philosophical discourse, from Plato and Aristotle to St. Augustine, Leibniz, Locke, Berkeley and Charles Sanders Pierce.

A key element of the semiotics paradigm in its contemporary form is the requirement for a "source", or a producer of "messages" that are "communicated" via some "channel" to a "receiver", or a "destination". In other words, it envisions a highly structured process rather like the basic paradigm in information theory. However, semiotics embraces all the elements of that process. Equally important, semiotics focusses on the functional properties and meanings of the "messages". It is concerned with the content, not the physical or statistical properties per se, as in traditional information theory. Although the semiotics paradigm rather obviously applies to human language and communications systems, it has also been applied by semioticians to communications processes in other living systems. There is even a nascent new inter-discipline called "biosemiotics" (Hoffmeyer 1997).

The control information paradigm is distinctive in three ways. First, it does not presuppose a discreet source of "messages" or structured "channels". In our paradigm, every aspect of the phenomenal world represents "latent" information that may be detected and used in a myriad of different ways in cybernetic processes, and its role may be entirely passive. Indeed, even the absence of something may be of informational significance to a cybernetic system.

Second, our focus is on the "user" -- a cybernetic system and his/her/its goals and capabilities. Control "information" is always defined in terms of the functional relationship between the source and the user. But most important, our paradigm provides a way of measuring the meaning of various "signs" in terms of one or more quantitative metrics. We have proposed a way of measuring the relative power and efficacy of semiotic processes in cybernetic systems. We believe that semiotics as a science can benefit from the use of our control information concept.

CONCLUSION

We believe that the concept of control information provides a new tool for analyzing cybernetic processes, and informational processes, both in nature and in human systems. It provides both a qualitative and quantitative measure of information in terms of the functional consequences that are produced by a given informational unit in a given context. Moreover, it has many practical applications; indeed, it is already used implicitly as a measuring-rod in many different fields, from advertising to politics and education. As we noted above, it also lends itself well to economic analyses. In sum, we believe that control information enriches Wiener's original vision by providing a new and more fruitful way of measuring the relationship between communication processes and control functions. We believe that control information provides the missing element in Norbert Wiener's cybernetic paradigm.

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FOOTNOTES

1. Actually, the use of feedback mechanisms in technological systems dates back to antiquity (see O. Mayr 1970). However, Wiener provided a broader framework for understanding feedback processes in relation to goal-directed behaviors of all kinds. Contemporary theorists often distinguish between evolved, internal purposiveness ("teleonomy") and an externally imposed purpose, or "teleology."

2. The other leading figure among the pioneers in cybernetics, H. Ross Ashby, was even less helpful. In his much-cited classic, *Design for a Brain* (1960[1952]), Ashby barely mentioned communications, and the term "information" was not even referenced in his index. Even the all-important concept of feedback merited only two index references. There are occasional allusions to information, however. Thus, in one place Ashby describes trial-and-error learning as a valuable part of "information gathering" for an animal, which he notes is essential to adaptation (p. 83). However, there is no explicit treatment of information in Ashby's book, much less the problem of measuring it.

3. A simple thought experiment can be used to illustrate. Imagine two alternative “paradigms.” In one case, there is a delicately-structured, heated crystal inside an "isolated" system with Gibbsian constraints (no gravity or other extraneous influences). It is in a highly ordered state and also has a certain heat content and available energy. Now imagine a second isolated system containing an identical crystal with the same available energy but in the form of a pile of disordered shards. Is there any difference in the ability of the two crystals to do work?

4. Maxwell's demon refers to a famous 19th century "thought experiment," since recounted in innumerable discussions of thermodynamics. Physicist James Clerk Maxwell proposed a means by which, supposedly, the Second Law might be violated. Maxwell conjured up a fanciful creature that would be stationed at a wall between two enclosed volumes of gases at equal temperatures. (The term "demon" was actually coined by a contemporary colleague, William Thomson.) The demon would then selectively open and close a microscopic trap door in the wall in such a way as to be able to sort out the mixture of fast and slow gas molecules between the two chambers. In this manner, Maxwell suggested, a temperature differential would be created that could be used to do work, thereby reversing the otherwise irreversible thermodynamic entropy.

We suspect that Maxwell never thought his successors would take his demon very seriously, but many have. This is why, in the 1920s, physicist Leo Szilard was impelled to argue, in a professional journal, that the energetic costs associated with the demon's efforts (he focussed on the gathering of "information") would cancel out any gains from the sorting process; the demon had to be part of the thermodynamic accounting. Then, in 1949, Leon Brillouin added the argument that, in order to be able to "see" the molecules, the demon would also need illumination. Following Szilard's lead, Brillouin stressed that the "information" required to do the sorting involved an offsetting (entropic) cost. Many other theorists have made similar arguments since (see especially the papers collected by Leff and Rex, 1990).

There are other objections as well. As shown in Kline (1997), the very notion that it could ever become possible to track and sort individual molecules in a volume of gas is scientifically and technically unfeasible. Another objection to Maxwell's paradigm, mostly overlooked, is that the demon would be attempting to derive work from a thermal gradient in a control mass with a fixed energy content (an isolated system). If, for example, the two volumes were hooked up to a heat engine coupled to a means for "recapturing" the energy from the work output, it would defeated by the Kelvin-Planck dictum which states, in effect, that you cannot create a perpetual motion machine; the output would not be completely reversible and the system would eventually wind down.

The fundamental problem with the Maxwell's demon paradigm is that it was not really an experiment in physics (thermodynamics) at all but a surreptitious -- albeit unacknowledged -- experiment in biology. Maxwell himself can be blamed for creating this muddle. In the famous and much-quoted passage from his 1871 book, *Theory of Heat*, in which he introduced his imaginary "being", Maxwell wrote that the Second Law is true "as long as we can deal with bodies only in mass, and have no power of perceiving or handling the separate molecules of which they are made up. But if we conceive a being whose faculties are so sharpened that he can follow every molecule in its course, such a being...would be able to do what is at present impossible to us" (quoted in Leff and Rex 1990:4). Setting aside the egregious implication that such a perceptual feat might ever become feasible, Maxwell then proceeded to make a serious conceptual error. He claimed that his hypothetical creature could "without the expenditure of work" create an energetic differential in a divided "vessel". That assertion effectively removed the demon at a stroke from the realm of realism. Of course, Maxwell was only using his metaphor as an illustration of the fact that "statistical methods" are important to micro-level thermodynamic analyses. He did not pose it as a serious theoretical problem. Unfortunately, many of his successors have taken it seriously; Leff and Rex (1990) provide an annotated bibliography with some 250 references, many of which are concerned either with exorcising or resurrecting the demon.

However, as an increasing degree of realism has been introduced into the debate, along with various doomed attempts to add technological improvements to molecular demons, the physics community has converted the demon experiment into a problem in information theory and, lately, into a pedagogical tool in introductory physics courses.

The ultimate failure of physicists to design a "feasible" Maxwell's demon highlights the fundamental problem associated with defining the evolutionary process in purely thermodynamic terms. Maxwell's demon shows us, inadvertently, why it cannot be done. In a nutshell, there is no way to operate the demon at a profit. Despite the claims of some physicists and biophysicists, the evolution of living systems can best be "explained" not in terms of the laws of physics (or the concepts of entropy and negentropy) but in terms of "bioeconomics". The laws of thermodynamics describe underlying physical conditions and constraints with which bioenergetic and human-made technological systems must cope, but they do not encompass or explain the "informed," purposive actions of cybernetic control systems. In living systems (and, by extension, in human technology), the locus of causation is not confined to the energetics; it is crucially dependent also on the actions of teleonomic/synergistic physical structures and activities; in order for living systems to function, "purposeful" work must be done to acquire and make use of available energy, which necessarily entails "extraction" or "production" costs. In effect, the structures and mechanisms associated with the capture and utilization of energy for purposive "work" introduce a new set of "bioeconomic" (and control) criteria into thermodynamic processes. This perspective suggests the need for such familiar economic concepts as capital investments, operating costs, efficiency, even amortization (consider, for example, the annual "retooling" by deciduous trees). So, Maxwell's classic model, even with the assistance of modern technology, is not a paradigm for progress. A much better model -- and this is the point -- is a cyanobacterium in sunlight. Nature has vastly improved on Maxwell's demon by developing a highly efficient available energy capturing system that regularly operates at a profit. (This subject is discussed in greater depth in Corning 2001.)

5. Another problem with defining information as equivalent to physical order is that it entails the same kind of semantic pettifoggery that is associated with the concept of "negative entropy." In fact, the term negative entropy is really a convoluted synonym for thermodynamic order. It means, literally, an absence of an absence of order. If information is "equivalent" to order/negentropy, then it is inextricably ties to available energy, or physical order of all kinds (or both), depending upon how the term negentropy is defined. If so, information is highly inflammable; it is "consumed" every time irreversible work is performed and every time entropy increases, for whatever reason.

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