Terrence W. Deacon

Shannon – Boltzmann – Darwin: Redefining information (Part I)

A scientifically adequate theory of semiotic processes must ultimately be founded on a theory of information that can unify the physical, biological, cognitive, and computational uses of the concept. Unfortunately, no such unification exists, and more importantly, the causal status of informational content remains ambiguous as a result. Lacking this grounding, semiotic theories have tended to be predominantly phenomenological taxonomies rather than dynamical explanations of the representational processes of natural systems. This paper argues that the problem of information that prevents the development of a scientific semiotic theory is the necessity of analyzing it as a negative relationship: defined with respect to absence. This is cryptically implicit in concepts of design and function in biology, acknowledged in psychological and philosophical accounts of intentionality and content, and is explicitly formulated in the mathematical theory of communication (aka "information theory"). Beginning from the base established by Claude Shannon, which otherwise ignores issues of content, reference, and evaluation, this two part essay explores its relationship to two other higher-order theories that are also explicitly based on an analysis of absence: Boltzmann's theory of thermodynamic entropy (in Part I) and Darwin's theory of natural selection (in Part II). This comparison demonstrates that these theories are both formally homologous and hierarchically interdependent. Their synthesis into a general theory of entropy and information provides the necessary grounding for theories of function and semiosis.

Truth is something we can attempt to doubt, and then perhaps, after much exertion, discover that part of the doubt is unjustified.
Niels Bohr

... only that which is absent can be imagined.
Marcel Proust

Re-conceptualizing information

The concept of information is a central unifying concept in the sciences. It plays critical roles in physics, computation and control theory, biology, cognitive neuroscience, and of course the social sciences. It is, however, employed somewhat differently in each, to the extent that the aspects of the concept that are most relevant to each may be almost entirely non-overlapping. Additionally, there are both highly technical and restricted uses of the term that while allowing precise quantitative analyses, entirely ignore the representational aspect of the concept that is its ultimate base, and is the foundational notion of semiotic theory. More seriously, the most precise and technical definition used in communication engineering, computational theory, and physics is potentially applicable to a vast range of physical differences that effectively could characterize almost any physical relationship of difference, even quantum differences. This promiscuity threatens to make it either so ubiquitous that it provides no insight into the physical distinctiveness of semiotic relationships, or else licenses flights of pan-psychic fantasy. For these reasons, clarifying and formally systematizing these variations of the information concept is not only a useful exercise but is essential to establishing a firm foundation for semiotic theory.

Without a grounding in a theory of information semiotic theories risk being merely descriptive taxonomies, lacking sufficient means to explain their causal efficacy or empirical status. Although not all semiotic relationships convey information, in the sense of previously unavailable content or novel representations, the possibility of semiosis is itself dependent on prior information conveying the constraints on dynamical organization that are sufficient to establish this interpretive dynamic. For an organism or mind to be able to interpret something as representing some object or content, it must already be organized with respect to that absent feature in some way or other, and that requires that information with respect to their relationship has already linked them, at least indirectly. But the nature of this dynamical linkage is not at all clear or simple. Cognitive science theories based on computational metaphors and phenomenological theories of mind based on linguistic and semiotic metaphors merely recapitulate the classic dualism of enlightenment philosophy because both leave information an undefined primitive, rather than an emergent dynamical relationship.

The current era is often described as the "information age", but although we use the concept of information almost daily without confusion, and we build machinery (computers) and network systems to move, analyze, and store it, I believe that we still do not really know what *it* is. In our everyday lives information is a necessity and a commodity. It has become ubiquitous largely because of the invention, perfection, and widespread use of computers and related devices that record, analyze, replicate, transmit, and correlate data entered by humans or collected by sensor mechanisms and produce correspondences, billings, sounds, images, and precise patterns of mechanical behavior. We routinely measure the exact information capacity of silicon, magnetic, or laser data storage devices. Scientists have recently mapped the molecular information contained a human genome, and even household users of internet communication are sensitive to the information bandwidth of the cable and wireless networks that they depend on for connection to the outside world. It is my contention, however, that we currently are working with a set of assumptions about information that are merely sufficient to handle the tracking of its most minimal physical and logical attributes but which are insufficient to understand either its defining representational character or its pragmatic value. These are serious shortcomings that impede progress in many endeavors from automated translation to the design of intelligent internet search engines.

In many ways, we are in a position analogous to the early 19th century physicists in the heyday of the industrial age (with its explosive development of self-powered machines for transportation, industry, timekeeping, etc.) whose understanding of energy was still laboring under the inadequate and ultimately fallacious conception of ethereal substances, such as *caloric*, that were presumably transferred from place to place to animate machines and organisms. The notion of information is likewise colloquially conceived of in substance-like terms, as for example when we describe "movement" and "storage" of information or talk about data being "wasted" in some process. The development of the general concept of energy, as a relation rather than a substance, took many decades to clarify, even though it was a defining feature of that era. It was ultimately tamed by recognizing that it was not a substance, but a difference that could give rise to either the potential for or the expression of non-spontaneous change. It was an abstraction from a process. But this abandonment of substantialist explanations did not result in the concept of energy becoming either epiphenomenal or mysterious. Both the conceptions of energy as ineffable ether and of substantial substance were abandoned for a dynamical account. Similarly, we will be required to give up substantialist thinking about information and representation in order to develop them into scientifically useful concepts. Neither the physical identification of information with pattern nor the phenomenological conception of an irreducible intentional relationship that is "always already there", will survive this reformulation.

Omissions, expectations, and absences

Explaining information requires an analogous shift of focus from substances to relationships and processes. But in the case of information, this is even more fundamental and more counterintuitive than for energy, because the very nature of information is a relationship between something present or proximate and something absent or distal. To put this in even more enigmatic terms: what makes something information is its relationship to something that it is not. This property is commonly what we mean when we say that information has sense or meaning as well as reference or (in philosophical terms) "intentionality" – often described as "aboutness". And this peculiar entanglement with something other or absent becomes even more confusing when we try to understand the causal status of information. We commonly recognize that what information is about – i.e. that which it is not – is the basis of its special causal power, such as when information about an impending storm causes one to close windows and shutters. In this regard, information is a fundamental feature of all teleological phenomena in which physical work is produced with respect to a represented end or embodied function. But this raises the troubling question: how can something not physically present be a cause of present physical changes?

The one thing common to all examples where something absent is causally significant is the presence of a habit, or a regularity,[1] with respect to which something missing can stand out. This is an important hint about how something not present can come to be significant and even causally efficacious. The term habit encompasses not merely a predictable behavior but, more

1 Note the analogy to physical work, which is dependent on a spontaneous gradient of thermodynamic change toward higher entropy to produce a local reduction of entropy in some linked domain.

generally, any tendency to change in a redundant way or to exhibit regularity or symmetry. Though we most often use the term habit to describe an organism's repetitive behaviors, or the behavior of people following a social convention, the broader sense of habit can be exemplified by the operation of a machine, or even by some naturally occurring regularity, like the predictable cycling of the ocean tides. The most general definition of habit does not even require anything like pattern or cyclicity, but merely a tendency to consistently exhibit some possible states more often than others. Even systems that appear mostly chaotic and yet are partly constrained in their behavior can offer some degree of predictability against which deviation is recognizable. In the most general sense, all regularities are the result of constraints that limit the scale, dimensions, or probabilities of interactions and interrelationships.

This highly general notion of *constraint on variety* is one of the core concepts of mathematical information theory (which will be discussed below), and as we will see, it also turns out to be relevant at every level of the information concept. It is with respect to some constraint that something absent or deviant can stand out, allowing that absence or deviance to become "content" and thereby acquire indirect efficacy.

To be more precise about how it is that something not present can nonetheless be a significant element in organizing the production of physical processes, we first need to distinguish between non-existence and absence. Simple non-existence, pure nullity – if such a thing can even be imagined – has neither extension nor substance. More commonly, however, our concept of not existing is framed in contrast to a presence: something missing as opposed to mere nothingness. Unlike nothingness, absence has extension, because it is bounded by contrast to what is present. Not only does an absence have a specific locus in space and time, it is often implicitly understood with respect to something quite specific that is missing. This often involves specific physical materials and properties that happen to be missing, such as the dirt missing from clothes after they've been washed, the hole at the wheel's hub, or the space within a container. In this contrastive sense, an absence can correspond to definite physical properties. This particular sense of absence is the sort of 'nothing' that can help us to make sense of information at many levels, and ultimately re-link the semiotic world to its physical foundations.

One way to begin to see how absence can be significant is to consider cases where absence itself is informative, as in cases of omission. To take just one example: after April 15th if a U.S citizen has not prepared and submitted a US tax return, it becomes a "missing" tax return. In a legal context which requires producing a tax return by this date, its nonexistence will set in motion events involving IRS employees coercing the delinquent taxpayer to comply. They may write and send threatening letters and might contact banks and credit agencies to interfere with the taxpayer's access to assets. So-called sins-of-omission can also have significant social consequences. Consider the effect of the "thank you" note not written or the RSVP request that gets ignored. Omissions in social contexts often prompt deliberations about whether the absence reflects the presence of malice or merely a lack of social graces. And we are all too familiar with omissions of preparation or attentiveness that can be the indirect cause of a disaster. The absence of foresight due to lack of appropriate knowledge or reasoning power – or just ignorance – can also be blamed for allowing "accidents" to occur that might otherwise have been avoided. Intuitively, then, we are comfortable attributing real world consequences to 'not thinking', 'not noticing', 'not doing', and so on. In these human contexts, then, we often treat presence and absence as though they can have equal potential efficacy.

These familiar examples are, of course, special cases that invert the general rule about information – something present that is taken to be about something not present – and yet they exemplify a critical point: *being about something need not be based on any intrinsic properties of the signal medium.* Indeed, this fact suggests that specific details of embodiment are often largely irrelevant. Omissions are only meaningful in the context of specific expectations or processes that will ensue if certain conditions are not met, or tendencies no longer impeded if some action is not undertaken to oppose them. Where there is a habit of expectation, a tendency that is intrinsic, a process that needs to be actively opposed or avoided, or a convention governing or requiring certain actions, the failure of something to occur can have definite consequences.

One might object that although this is our colloquial way of describing these relationships, we do not actually believe that absence is causative in these cases. We tend to consider only the habit itself as causally relevant, and yet we need also to consider the fact that the habit in question is organized around an expectation; i.e. something not currently present which in some way in the past contributed to this organization. Following up on this important hint about the origins of habits predicated on absences will need to wait we have a chance to consider the logic of evolutionary processes, but for our present purposes it is important to simply focus on the nature of physical organization with respect to something absent. This concept of organization with respect to something not present or excluded is not just relevant to ideas of representation and intentionality. It is also fundamental to the very concept of function that we apply to man-made machines and organisms.

Consider machines. While we tend to define the *function* of a machine as something it accomplishes, this definition makes it appear as though the function is something added over and above the material-mechanical attributes of the machine. If, however, we avoid introducing implicit teleology and human purpose into the description, a machine's function is best described in terms of something *less* than the sum of all its parts and the physical laws that govern their interactions. In fact, a machine's function depends on the realization of some of its possible states and behaviors and the prevention of all other states and behaviors. Though we tend to define function in terms of what the machine is designed to achieve, because that is the purpose for which it was built, this notion of function is entirely parasitic on human mentality, and merely begs the question of the efficacy of the nonexistent state of a represented goal. But setting aside the role of mental processes for the moment, we can see that another sense of something absent is critical to the functionality of the machine. It is what the device is *prevented* from doing that is physically critical to guaranteeing this function.[2]

This negative view of function is easily recognized in the case of machine failure. When constraints break down, and previously restricted states or behaviors of the machine become possible, functionality is degraded. So, for example, when the bolts holding engine parts together loosen, allowing moving parts to move inappropriately, catastrophic loss of function can occur. Though the laws of physics and chemistry have not changed and nothing new has been introduced, the appearance of these new behaviors introduces something else, something not-quite-physical: the failure to function. Thus function is provided by a limitation imposed on the possible physics of the machine. It is *not* the result of something *in addition* to the material of its construction, the energy of its animation, or the physical laws that govern it since, when the machine is broken, all these remain as before.

2 This figure/ground reversal of logic was eloquently described by Michael Polanyi in his influential paper "Life's irreducible structure" (1968). He describes constraints on the range of component interactions as the *boundary conditions* of the system, and argues that function arises with the imposition of boundary conditions.

In effect, then, what gets lost when a machine ceases to function is some limitation on what can happen. But the loss of a limitation (i.e. some increase in degrees of freedom) is a paradoxical sort of loss. And the converse – creating function by eliminating a class of dynamical possibilities – is an equally counterintuitive way of thinking about function, but this is the critical figure/background flip that we will need to consider. Nor is it just machines that exhibit this paradoxical negative existence; life does as well. Disease and death are not the diminishment or loss of some special essence; they are a gain in degrees of freedom. Diverse spontaneous chemical reactions and organismal activities that are prevented or precisely controlled during life are no longer constrained after death. So life is as much about what is prevented from occurring – what it is not – as it is about the special improbable habits that we associate with it.

So this same negative logic of "organization with respect to something not present" is the essence of biological function as well as machine function. It is, for example, implicit in the relationship between properties of visible light and the precise constraints on vertebrate-eye anatomy, or between the viscosity of water and streamlining of fish, shark, and dolphin bodies. In this sense, we can think of a biological adaptation as the complement to some property or regularity present in the environment of the organism. From ancient times, this parallel has suggested that organisms must have been designed, like machines, by some extrinsic miraculous designer who conceived of this purpose and fashioned the organism for this purpose. But, except for the rhetoric of fringe religiously-motivated critics, we have come to understand another way that such self-perpetuating functional constraints can come into existence: evolution by natural selection. Whereas machines and linguistic signs derive functionality and intention by a kind of parasitism on human purposiveness, the living functions of the body and mind are intrinsically end-directed, and not derived from prior representation of these ends. This suggests that a comparison of biological adaptations to mental representations may also provide some useful insights for exploring how organization with respect to absence can arise of its own accord, and thus how this critical defining feature of information can be understood.

To summarize, many phenomena can be described as having an existence partially defined with respect to something physically absent: function, adaptation, agency, purpose, reference, meaning, value, experience. What these and all intentional relationships share is the property of existing with respect to something else, something not immediately present, and possibly something not in existence or even possible. I propose the term *constitutive absence* to indicate this generic property characterizing everything from biomolecular function to semiotic activities. Constitutive absence can be defined as *the property of being structurally or dynamically organized with respect to (or by virtue of) attributes present (also potential or projected) in some extrinsic object or process.* It characterizes mental processes whose existence and organization is constituted by their relationship to external objects and events or to possible or even imaginary states of affairs. It can also describe a significantly wider class of systems, including biological adaptations and machines and tools designed for given human purposes. Exploring the commonalities between the various phenomena exhibiting constitutive absence and the analytical tools that have been developed for dealing with such relationships in three different fields of study – engineering, thermodynamics, and evolutionary biology – will provide the first step toward demonstrating how the constitutive absences relevant to physical systems are connected with those which underlie semiotic processes.

With this much as background, we are now in a position to consider a three-tiered analysis of information. The analysis begins with a reconsideration of the concept of entropy as formulated in thermodynamics and in information theory. It then explores the necessary interdependence between thermodynamics and information and shows how this interdependence contributes to the development of reference. Finally it shows how the relationship between thermodynamic work and logical signal generation can be augmented via Darwinian logic to specify reference to assure pragmatic relevance in a given context. This three-tiered analysis, in turn, suggests how we might approach a dynamic theory of semiosis that addresses the relationship of intentionality to underlying physical processes, the source of the normative character of information, and its relationship to end-directed functional organization such as exhibited by organisms.

Two entropies

Recognizing the importance of regularity (habit) and constraint for understanding this negative logic behind the concepts of function and representation, we begin by considering the contribution of nature's most basic habit: the spontaneous tendency for entropy to increase in physical systems. Entropy is often defined as the measure of disorder in a system, so this "habit" is also often described as the tendency for disorder to increase spontaneously. Such definitions can be a bit misleading, however, since we often consider order as something that requires an external observer to define. Perhaps a more accurate (and more technically precise) definition is that the entropy of a collection of elements or features is a measure of how uncorrelated they are from one another in some respect of other. So, in physical systems undergoing change, correlation tends to spontaneously decrease over time. This tendency for interacting elements (e.g. colliding molecules) to spontaneously become increasingly uncorrelated in their properties (e.g. movements) over time was independently described by Rudolph Clausius and James Clerk Maxwell in the 1860s, and is the statistical basis for the Second Law of Thermodynamics.

The Second Law is a necessary consequence of the fact that there are vastly more higher entropy states of a given system than there are lower entropy states. Said another way, there exists an extreme asymmetry in the statistics of the distribution of possible consequences, with far more options for less correlated than more correlated relationships between components. This "law" is unlike the determinate laws of physics (like those of Newton) because the actual course of things could, in principle, proceed otherwise (e.g. billiard balls poured randomly onto a table could spontaneously happen to all collide in just such a pattern that they ended up arranged into a neat triangle). It is just astronomically improbable that they will.[3] All other things being equal, then, a state near maximum entropy will transition to another state near maximum entropy vastly more often than to a state of reduced entropy. We might caricature this as nature's egalitarian bias; favoring equal opportunity for all possible states of components.

The term *entropy* was coined by Rudolf Clausius and become the central concept in his 1865 ground-breaking analysis of the relationship of mechanics to thermodynamics. Such ideas were later synthesized by Ludwig Boltzmann (1866), among others, to produce our modern understanding of thermodynamic processes. Boltzmann was also influential in recognizing that the correlation and decorrelation of component parameters that is the basis for entropy could be described in terms of order and disorder, respectively. We will therefore refer to this conception of thermodynamic entropy as *Boltzmann entropy*.

3 This is not to claim that the triangular arrangement after the balls are racked and ready for a new game is any more improbable than any other singular highly specific arrangement, but at higher levels of description this symmetry quickly breaks down. For example, there are far more arrangements where the balls are more evenly distributed around the table than clustered together, and more clusters where the balls are just close versus all touching, and so on, for different levels of global descriptions.

This reliably asymmetric habit of nature provides the most basic background with respect to which a specific absent influence can be identified. The reason is simple: When something is highly reliably present, like disorder, its absence typically means that there has been some external interference to push it away from this most probable state. So when something that normally occurs suddenly fails to occur, it typically means that something external is influencing it. Hence the relentless reliability of the second law of thermodynamics provides the background for noticing that something non-spontaneous has occurred. If events do not proceed according to the expected asymmetrical trend (toward entropy increase), it can be inferred that something external has done work to divert it.[4]

A second use of the term *entropy* has become widely applied to the assessment of information, and for related reasons. In the late 1940s the Bell Labs mathematician Claude Shannon demonstrated that the most relevant measure of the amount of information that can be carried in a given medium of communication (e.g. in a page of print or in a radio transmission) can be understood in terms of an analogous statistical relationship. He based his analysis on the model of a transmission channel such as a telephone line with a fixed limit to the variety and rate of signals that it could carry. This model system will be used throughout the discussion to be consistent with Shannon's terminology, but the analysis equally applies to anything able to convey information, from text on a page to clues used in a criminal investigation.

According to Shannon's analysis (of channels with discrete signals[5]) the quantity of information conveyed at any point is the improbability of receiving a given transmitted signal, determined with respect to the probabilities of all possible signals that could have been sent. Because this measure of signal options is mathematically analogous to the measure of physical options in Boltzmannian entropy, Shannon also called this measure the "entropy" of the signal source.[6] In this paper I will call it *Shannon entropy* to distinguish it from Boltzmann entropy.

4 Indeed, this is what makes self-organizing dynamics so intriguing and makes living dynamics often appear planned and executed by an external or invisible agency.

5 Shannon's analysis considered many different systems including discrete and continuous channels in order to demonstrate the generality of the principle. Though the examples described here are the simplest examples involving discrete signal sources, the general principle is the same for all cases.

6 This terminology was apparently suggested by the mathematician John Von Neumann.

Consider, for example, a coded communication sent as a finite string of alphanumeric characters. If each possible character can appear with equal probability at every point in the transmission, there is maximum uncertainty about what to expect.[7] This means that each character received reduces this uncertainty by that probability and an entire message reduces the uncertainty with respect to the probability that any possible combination of characters of that length could have been sent. The amount of the uncertainty reduced by receiving a signal is Shannon's measure of the maximum amount of information that can be conveyed by that signal. In other words, the measure of information conveyed involves comparison of a received signal with respect to possible signals that could have been sent. If there are more possible character types to choose from or more possible characters in the string, there will be more uncertainty about which will be present where, and thus each will potentially carry more information. Similarly if there are fewer possible characters, fewer characters in a given message, or if the probabilities of characters appearing are not equiprobable, then each will be capable of conveying proportionately less information. The entropy of a communication channel with a fixed rate of transmission, or of a page of typed characters, or of some other patterned medium, is in this way an estimate of how much information it can possibly carry. This analysis can be applied to a radio signal, a page of text, or even the distribution of objects in a room used as a potential sign.

Shannon's analysis of information capacity provides another example of the constitutive role of absence. According to this way of measuring information, it is not intrinsic to the received communication itself; rather, it is a function of its relationship to something absent; the vast ensemble of communications that could have been sent but weren't. Without reference to this absent background of possible alternatives, the amount of potential information of a message cannot be measured. In other words, the background of un-chosen signals is a critical determinant of what makes the received signals capable of conveying information. No alternatives = no uncertainty = no information.

This suggests an interesting analogy with the notion of machine function. In an abstract sense we might, for example, consider the amount of information embodied in the design of a machine as the measure of the arrangements and

7 Thus the probability of appearance of each character at each position is maximally uncorrelated with all others, as is the movement of each molecule in a gas at equilibrium. This justified calling both conditions maximum entropy.

movements of parts that could have been realized with respect to those actually allowed by design (though actually measuring such design entropy would likely prove infeasible). It also suggests a further analogy to thermodynamics. A thermodynamic system at equilibrium is in its most probable state, and is unavailable to do any work. Only a thermodynamic system in an improbable state (i.e. far from equilibrium) is able to be used to do physical work and the degree of improbability corresponds to the quantity of this potential to do work. The parallel negative logic used to define information, function, and work will turn out to be critical to a full account of the nature of information (see below).

It should be pointed out, at this point, that we are only able to measure *potential* information carrying capacity in this way. It is irrelevant to this analysis whether or not a given signal or message is about anything at all. Of course, just having the potential to convey a given amount of information, does not itself make something information in the normal sense of that word.[8]

The analogy to thermodynamic entropy breaks down, however, when we consider that Shannon entropy does not generally increase spontaneously in most communication systems, and, there is no equivalent to the 2nd law of thermodynamics when it comes to the entropy of information. The arrangement of units in a message does not necessarily "tend" to change toward equiprobability. And yet something analogous to this effect becomes relevant in the case of real physically embodied messages conveyed by real mechanisms (such as a radio transmission or a computer network). In the real world of signal transmission, no medium is free from the effects of physical irregularities and functional degradation, an unreliability resulting from the physical effects of the 2nd law. Hence both kinds of entropy are relevant to the concept of information, though in different ways. The Shannon entropy of a signal is the probability of receiving a given signal from among those possible, and the Boltzmann entropy of the signal is the probability that a given signal may have been corrupted.

A transmission affected by such thermodynamic perturbations that make it less than perfectly reliable will introduce an additional level of uncertainty to

8 In order to avoid this equivocal usage it would be helpful to have a different word, specifically referring to this potential that exists, irrespective of any content or interpretation. The pioneering cybernetic theorist W. Ross Ashby suggested using the term "variety" in this context to avoid these confusing equivocations. Unfortunately, the ambiguous use of "information" for both meanings has persisted.

contend with, but one that decreases information capacity. An increase in the Boltzmann entropy of the physical medium that constitutes the signal carrier corresponds to a decrease in the correlation between sent and received signals. Although this does not decrease the signal entropy it reduces the amount of uncertainty that can be removed by a given signal and thus reduces the information capacity. This is of course just a technical way of saying that a noisy medium of communication is less efficient in transmitting information.

But this identifies two contributors to the entropy of a signal, one associated with the probability of a given signal being sent and the other associated with a given signal being corrupted. This complementary relationship is a hint that the physical and informational uses of the concept of entropy are not merely analogical uses of the same term. But the connection is subtle, and its relationship to the way that a signal conveys its information "content" is even more subtle, as we shall see.

To summarize the present points, we can identify three general rules about the nature of information and its relationship to the material-energetic processes on which it is dependent:

1) *Information potential:* Information is dependent on the physical features of a communication channel or (more generally) a sign medium and so the capacity of that channel or medium to assume different states (its maximum possible Shannon entropy) determines the maximum amount of information it can convey.

2) *Physical basis of information:* The Shannon entropy of a communication channel or sign medium is a function of the variety of states it can assume along with the degree of their causal independence from one another. This in turn can be described in terms of Boltzmann entropy.

3) *Information as absence:* The maximum potential information that a signal or sign can convey must be measured with respect to signals or signs that were not produced. It can only be defined and quantified with respect to the probability of these unrealized possibilities. Even in noisy conditions where an unreliable medium does not allow complete reduction of uncertainty from the maximum Shannon entropy, any degree of reduction provides a measurable level of information.

Information and reference

Warren Weaver, who wrote a commentary article that appeared in a book presentation of Shannon's original paper (Shannon and Weaver 1949), commented that using the term information to describe the measure of the unpredictability reduced by a given signal is an atypical use of the term. This is because Shannon's notion of information is agnostic with respect to what a signal is or could be about. This agnosticism has led to considerable confusion outside of the technical literature because it is almost antithetical to the standard colloquial use of the term. As Collier (2003) comments: "The great tragedy of formal information theory is that its very expressive power is gained through abstraction away from the very thing that it has been designed to describe". Because Shannon was interested in measuring information for engineering purposes, he concentrated exclusively on the properties of transmission processes and communication media, and ignored what we normally take to be information, i.e. what something tells us about something else that is not present in the signal medium itself. This was not merely an arbitrary simplification, however, because the same sign or signal can be given any number of different interpretations. Dirt on a boot can provide information about anything from personal hygiene to evidence about sort of geological terrain a person recently visited. The properties of some medium that give it the potential to convey information, do not determine what it is about, they merely make reference possible. But why should a decrease in sign or signal uncertainty possess this capacity?

In order to provide a finite measure of the information potential of a given signal or channel, Shannon had to ignore any particular interpretation process, and stop the analysis prior to including any consideration of what a sign or signal might be about. This is because what is conveyed – the content or reference we normally use the term information to designate – is not merely a function of this reduction of Shannon entropy, it also depends on a separate interpretation process and whatever process produced the modification in this medium that accounts for this reduction. Exploring the relationship between Shannon entropy and these two physical processes can shed light on the reason why change in entropy is critical to information.

This is where the relation between Shannon and Boltzmann entropy turns out to be more than merely analogical. A fuller conception of information requires that these properties be considered with respect to two different levels of analysis of the same phenomenon: the formal characteristics of the signal and the material-energetic characteristics of the signal. The key point is that, despite its negative character, information transmission and interpretation must be a physical process involving a material or energetic substrate which constitutes the channel, storage medium, sign vehicles, etc. And physical processes are subject to the laws of thermodynamics. So the basis for the interdependence of Shannon and Boltzmann entropy can be stated in simple form as follows: *a reduction of either Shannon or Boltzmann entropy does not tend to occur spontaneously, so when it does occur it is evidence of the intervention of an external influence.*

Returning to Boltzmann entropy, if within the boundaries of a physical system such as a chamber filled with a gas, a reduction of entropy is observed, one can be pretty certain that something not in that chamber is causing this reduction of entropy. So being in an improbable state or observing a non-spontaneous change toward such a state is evidence for extrinsic perturbation; i.e. work done to perturb the system. Analogously, in the case of Shannon entropy, no information is provided if there is no reduction in the uncertainty of a signal (i.e. if you cannot in any way distinguish signal from noise). But reduction of this entropy indicates that outside constraints have been imposed on the sign/signal medium. This is obvious in the case of a person selecting the transmission, but it is also the case in more subtle conditions. Consider, for example, a random hiss of radio signals received by a radio antenna pointed toward the heavens. A normally distributed radio signal represents high informational entropy, the expected tendency in an unconstrained system, which for example might be the result of random circuit noise. If this tendency were to be altered away from this distribution in any way, one could assume that there was some extrinsic nonrandom factor at work. The change could be due to an astronomical object emitting a specific signal, or if neither random nor highly regular it might even suggest a transmission by an extraterrestrial race. In either case, if we should encounter such a signal it would point us toward the likelihood that this can be informative about something other than the signal detection circuit, something not present in the system itself but rather something outside altering and thereby imposing non-spontaneous constraint on the otherwise uncorrelated jumble of signals. The reduction in Shannon entropy of the physical signal indicates that some external physical influence has done work to alter it. In simple terms, the brute fact of this deviation is the basis for using the signal as information about something else. Moreover, the form of this deviation is the only basis we have for choosing which extrinsic influence of the infinity of possible factors that could be affecting it is the one that is. The form of the deviation is a clue to help us with another process of Shannon entropy reduction: *a reduction in our uncertainty about which of the many possible extrinsic physical influences is the relevant one.*

Thus, to summarize: something other than that feature of the medium that conveys the information – the specific form of the reduced Shannon entropy – provides evidence of another absent physical phenomenon – whatever performed the work on the signal to effect this reduction. Information is made available when the state of some physical system is different from what would be expected were its features to be the result of random influences or complete physical isolation, but what that information can be about depends on the form of this reduction.

So not only is the Shannon entropy of an information bearing process important to its capacity, its physical dynamics with respect to the physical context in which it is embedded is important to the determination of what it can be about. Reference is provided to the extent that an external perturbation of its physical states alters it from a less constrained state to a more constrained state, thus reducing its Shannon entropy. The extent to which this occurs is a measure of the quantity of information that can be conveyed. The specific form of this reduction is the means by which an interpretation process can reduce the Shannon entropy of the range of possible phenomena it could be about. In other words, what we might now call "referential information" is a second order form of information. In purely physical terms this can be described as a coupling between two systems' states or dynamics so that the behavior of one will partially re-embody some aspect of the regularity or constraints exhibited by the other with respect to their possible modes of interaction. Through this transfer of form, then, a signal can be seen as mediating the transfer of constraints from one system to another. But as we have seen above, constraints are not something added, but something not expressed. What is transferred is in effect an absence.

A first hint of the relationship between information as form and as a sign *of* something is exemplified by the role that pattern plays in each of these analyses. In Shannon's terms pattern is redundancy. From the sender's point of view, any redundancy (defined as predictability) of the signal has the effect of reducing the amount of information that can be sent. In other words, redundancy introduces a constraint on channel capacity. Less information can get transmitted if some transmissions are predictable from previous ones or if there are simply fewer alternatives to choose from. From the receiver's point of view, however, there must be some redundancy with what is already known for information to even be assessed. In other words, the context of the communication must already be redundantly structured. Both sender and receiver must share the set of options that constitute information.

Shannon realized that the introduction of redundancy is also necessary to compensate for any unreliability of the medium. If the reliability of a given sign or signal is questionable this introduces an additional source of unpredictability that does not contribute to information; it is described as noise. But just as redundancy reduces the unpredictability of signals, it can also reduce the unreliability of the vehicle of the information, if there is redundancy in the message being transmitted. In the simplest case, this is accomplished by resending the signal. Because noise is by definition not constrained by the same factors as is the selection of the signal, each insertion of a noise-derived signal error will be uncorrelated with any other, but independent transmission of multiple identical signals will be correlated by definition. In this way, noisy components of a signal or received message can be detected and replaced. But error-reducing redundancy can be introduced by means other than by signal retransmission. In a language like English, only a fraction of possible letter combinations are utilized and the probabilities of different letters can also be very different. More critically, grammar and syntax limit appropriate and inappropriate signals even further, and finally the distinction between sense and nonsense limits what words and phrases are likely to occur in the same context. This internal redundancy of written language makes typos relatively easy to identify and correct. Redundancy as a means of information rectification is also relevant to second order information. Thus, even if the specific form of the signals differs, as when one hears multiple independent reports by observers of the same event, the redundancy in the content of two messages can serve this same function. To be more precise, this is because there is redundancy in how the entropy of possible interpretations has been reduced in each, even though there will also be uncorrelated differences as well.

So, whereas redundancy decreases information capacity, it is also what makes it possible to distinguish information from noise, both in terms of the signal and in terms of what it conveys.

Three relevant conclusions can be drawn from this analysis with respect to the problem of referential information and its embodiment:

4) *Ground of reference:* What a signal can *indicate*[9] is dependent on the physical interaction of a signal medium with some relevant features of its physical context and the extent to which this changes the Shannon entropy of the received signal.

5) *Reference = open system:* A reduction in the Shannon entropy of a sign/signal medium is formally analogous to a thermodynamic system being shifted away from equilibrium. In both cases the change is evidence of work imposed from an external locus. This extrinsic relationship is the physical basis of referential information.

6) *Constraint and absence:* Both the reference conveyed (5) and the ground of the reference (4) of a signal are functions of something not present, which is reflected in reduced Shannon entropy of the signal. That which is explicitly *not* present is the effect of constraint, and constraint is a boundary condition; something imposed from outside the system under consideration. Referential information is thus a function of the transfer of constraints.

What we can conclude, at this point, is that the referential information that any sign or signal provides is not an intrinsic feature, but a function of extrinsically imposed constraints. The referential information is in this sense inferred from a formal characteristic embodied in the relationship between those signal features that are present and those that are absent. These formal characteristics are expressed in the signal in terms of what is not included but could have been.

Interpretation

What is so far missing from this analysis is an account of the interpretation process itself, without which the determination of reference remains undefined. Expanding the concept of information to fully account for reference requires not only recognizing the way a signal medium is physically embedded in a

9 With respect to semiotic theory, it is relevant to reiterate at this point that the concept of information is effectively concerned with what C. S. Peirce would describe as indexical forms of reference. Icons do not in this sense provide information about some object of reference, they directly embody certain of the constraints also embodied by their "object" of reference, but without physical influence, and symbols are only informative when they are coupled via indices to extra-symbolic contextual phenomena (see discussion in Deacon 2003).

context that can alter its entropy – producing the Shannon-Boltzmann understanding of referential information, above – but also how the possible form of that connection is incorporated into a process organized to make use of the information. In other words, the question of what constitutes an interpretation process is intimately connected with the concept of function and use. And as we saw above (in the discussion of the relationship between machine function and physical constraint), function also requires a negative characterization. So it should not surprise us to discover that information and function are intimately related. It also introduces a new feature into the characterization of information – a *normative* feature. The interpretation of a potential source of information can be accurate or inaccurate, correct or incorrect, useful or useless. Information is not just pattern and difference, it is pattern about something for some end, and with respect to that end some things will be conducive and some are detrimental.

For engineering purposes Shannon's analysis could not extend further than an assessment of the information carrying-capacity of a signal medium, because to do so would introduce an infinite term into the quantification; an undecidable factor. What is undecidable is where to stop with the analysis of the Boltzmannian interactions that contribute the constraints that convey some specific referential association. There are innumerable points along a prior causal history culminating in the modification of the sign/signal medium in question that could be construed to be the relevant reference. Which of these is the signal about? And what is it about the interpretation process that determines this?

As everyday experience makes clear, what is significant and what is not depends on the context of interpretation, the capacity to follow the trace to the relevant source of constraint, and the usefulness of doing so. So in different contexts and for different interpreters the same sign or signal may be taken to be about very different things. How is one feature selected by the interpretation process, and how is this given some likelihood of being accurately linked? In brief, the selection of a *specific* ground of reference – which constitutes the process of interpretation – is a function of the way this signal constrains and influences subsequent signal production/transmission processes, and how these have been constrained in the process of interpretation. This affects how these future information transmission functions will fit within roughly the same context as that which influenced the signal in question. As we will see below, this relationship is essentially analogous to natural selection.

So, although the physical embodiment of a communication medium provides the concrete basis for reference, its physical embeddedness also opens the door to an open-ended lineage of potentially linked influences. To gain a sense of the openness of the interpretive possibilities, consider the problem faced by a detective at a crime scene. There are many physical traces left by the interactions involved in the critical event: doors may have been opened, furniture displaced, vases knocked over, muddy footprints left on a rug, fingerprints on the doorknob, filaments of clothing, hair and skin cells left behind during a struggle, and so on. In this example, there is one complex event reflected in these signs. But for each trace there may or may not be a causal link to this event, and each will also have a causal history that includes many other influences. The causal history reflected in the physical trace taken as a sign need not be relevant to any single event, and which of the events in this history might be determined to be of pragmatic relevance can be different for different interpretive purposes and differently accessible to the interpretive tools that are available. This yields another stricture on the information interpretation process:

7) *Scope of reference:* The causal history contributing to the constraints imposed on a given medium limits – but does not specify – what its information can be about. Which point in this causal chain is the relevant object of reference is not determined; only some linkage to a causal history is provided by the immediate signal-context interaction.

In the late 19th century world of the fictional detective Sherlock Holmes there were far fewer means available to interpret such physical traces. Even so, to the extent that Holmes had a detailed understanding of the physical processes involved in producing each trace, he could use this information to extrapolate backwards many steps from effect to cause. This capacity is greatly augmented by modern scientific instruments that, for example, can determine the chemical constitution of traces of mud, the manufacturer of the fibers of a sweater, the DNA sequence information in a strand of hair, and so on. With this expansion of interpretive means there has been an increase in the amount of information that can be extracted from the same traces. These traces contain no more physical differences than they would have in the late 19th century, it is simply that more of these have become interpretable, and to a greater depth. This enhancement of interpretive capacity is due to an effective increase in the *interpretable* Shannon entropy of the signal. But of course the signal hasn't changed, the interpretation process has. How can the interpretation change the entropy of a signal source?

Although from an engineer's perspective, every possible independent physical state of a system must be figured into the assessment of its potential Shannon entropy, this is an idealization. What matters are the distinguishable states. The distinguishable states are determined with respect to an interpretive process that itself must also be understood as a signal production process with its own potential Shannon entropy. *In other words, one information source can only be interpreted with respect to another information production process.* The maximum information that can be conveyed is consequently the lesser of the Shannon entropies of the two processes. If the receiving/interpreting system is physically simpler and less able to assume alternative states than the sign medium being considered, or the relative probabilities of its states are more uneven (i.e. more constrained), or the coupling between the two is insensitive to certain causal interactions, then the interpretable information will be less than the potential information of the source. This, for example, happens with the translation of DNA sequence information into protein structure information, since there are 64 possible nucleotide triplets (codons) to code for 20 amino acids. Only a fraction of the possible codon entropy is interpreted to the amino acid sequence of a protein.[10] Because of this, scientist using DNA sequencing devices can discern more about the phylogeny of an organism than is reflected in its protein structure. This limitation suggests two interesting analogies to the thermodynamic constraints affecting work:

8) *Transfer constraint:* The combined interpretable Shannon entropy of a chain of systems (e.g. different media) through which information is transferred can be no greater than the channel/signal production device with the lowest entropy value. Each coupling of system-to-system will tend to introduce a reduction of the interpretable entropy of the

10 This does not necessarily mean that there is a loss of functionality accompanying this reduction. Just the opposite is true. The functional features of protein molecules are related to their three dimensional structure, which is a secondary consequence of the amino acid sequence. So a number of other correlated features of amino acids and their structural interactions with one another give proteins a much higher available Shannon entropy than the DNA that codes for the sequence, and consequently contribute to an amplification of information from genome to cell chemistry.

signal, thus reducing the difference between the initial potential and final received signal entropy.

9) *Degradation of reference:* Information capacity tends to be lost in transfer from medium to medium, and with it the specificity of the causal history that it can be about. Since its possible reference is negatively embodied in the form of constraints, what a sign or signal can be about tends to degrade in specificity spontaneously with transmission or interpretation.

This also means that, irrespective of the amount of information that can be embodied in a particular substrate, what it can and cannot be about, also depends on the specific details of the medium's modifiability and its capacity to modify other systems. We create instruments (signal receivers) whose states are affected by the physical state of some process we wish to monitor and use the resulting changes of the instrument to extract information about it, by virtue of its special sensitivities to its physical context. The information it provides is thus limited by the instrument's material properties, which is why the creation of new kinds of scientific instruments can produce more information about the same objects. The expansion of reference that this provides is implicit in the Shannon-Boltzmann logic. So while the material limits of our media are a constant source of loss in human information transmission processes, it is not necessarily a serious limitation in the interpretation of natural information sources, such as in scientific investigations, because in nature there is always more Boltzmann entropy embodied in the object or event treated as a sign, than current interpretive means can ever capture.

This interesting open-ended potential of the interpretability of natural signs illustrates another key point about interpretation. Iterated interpretation of the same source using varying interpretive processes with different causal architectures can be a source of higher-order error correction; i.e. with respect to reference.

Conclusions to Part I

The analysis so far has exposed a common feature of both the logic of information theory (Shannon) and the logic of thermodynamic theory (Boltzmann). This not only helps explain the analogical use of the entropy concept in each and also explain why it is necessary to link these approaches into a common theory to begin to define the referential function of information. Both these formal commonalities and the basis for their unification into a theory for the referential ground of information depend on a focus on a dependence on a relationship to absence. In the case of classic information theory, the improbability of receiving a given sign or signal with respect to the background expectation of its receipt compared to other options defines the measure of potential information. In the case of classic thermodynamics, the improbability of being in some far from equilibrium state is a measure of its potential to do work, and also a measure of work that was necessarily performed to shift it into this state. The linkage between these two theories hinges on the materiality of a given communication medium (e.g. the constitution of its sign and/or signal medium). Something becomes a potential source of information to the extent that its presence has some degree of uncertainty, but as a physical medium, being in an improbable state can be reliably attributed to some extrinsic interference. Another way to put this is that physical work is required to modify a sign or signal process away from its a priori probability distribution. So a sign/signal with any given Shannon information capacity has achieved it due to extrinsically imposed physical (thermodynamic) work. This necessary dependency is what can be called the *ground* of reference for an information source. In semiotic terms, this, in effect, describes the most basic kind of indexicality, though it can be extended to handle more indirect physical linkage as well.

Up to this point of the analysis it has been assumed that the relationships being described have involved signs and signals, and not merely physical events chosen at random. But in fact, *none* of the criteria specified so far actually distinguish events and objects that convey information from those that do not. In one sense this is a necessary feature. Any physical difference *can* be interpreted as information about something, whether it is the mud on someone's shoes or microwave radiation emitted almost uniformly from the background of the universe. What makes something information is not something intrinsic, but something extrinsic to its immediate properties and even its causal history. It is a difference that is interpreted to refer to, or mean, something with respect to some functional consequence. This might suggest that, at this stage, our discussion will need to introduce mentalistic assumptions and undefined homunculi to cross the threshold into semiosis. Although this has been a common strategy – one that typically causes the natural sciences to part company with the semiotic sciences and humanities – fortunately, this is not necessary.

Though any physical difference can become significant and provide information about something else, this requires that – as Gregory Bateson quipped – it is a difference that *makes* a difference, or perhaps more colloquially a difference that matters. It is interpretation that makes something matter, and turns mere difference with respect to some ensemble of alternative possibilities not present into information about something else not present. Explaining how an interpretation process can be organized so as to produce this sort of tripartite relationship between expectations and absences is therefore the crucial final step necessary to fully define information. In other words, we must explain the process by which information can be generated *de novo*.

In Part II of this essay (forthcoming in the next volume of Cognitive Semiotics) I will argue that the basic logic of this process must take the form of a version of natural selection. This can also be understood as formally analogous to both Shannonian and Boltzmannian entropy reduction at a higher level of analysis, involving interpretive processes instead of signals. In biological terms, natural selection involves the reduction of variety in the intrinsic characteristics of a population of organisms, determined by their fittedness (aka correspondence) to a given extrinsic environmental context. This defines a means for assessing adaptive information analogous to the way the reduction of Shannon entropy points to an outside influence. An evolutionary process does not merely transmit information into the future; it generates it dynamically, and defines current normative features of information (i.e. the potential for error or inaccuracy) in terms of the generative dynamics of organism function that arise from this process. By generalizing this third level of dynamical-system entropy-reduction beyond just biological evolution, we will be able to precisely define the informational basis for semiosis.

References

Ashby, W. R. (1956). *An Introduction to Cybernetics*. London: Chapman & Hall.

Boltzmann, L. (1866). The Second Law of Thermodynamics (Trans. P. Foulkes). Reprinted in B. McGuinness (Ed.), *Ludwig Boltzmann: Theoretical Physics and Philosophical Problems, Selected Writings* (pp. 13–32). Dordrecht: Reidel Publishing Co., 1974.

Clausius, R. (1865). *The Mechanical Theory of Heat – with its Applications to the Steam Engine and to Physical Properties of Bodies*. London: John van Voorst. Collier, 2003.

Collier, J. (2003). Hierarchical Dynamical Information Systems With a Focus on Biology. *Entropy* 5, 100–124.

Deacon, T. (2003). Universal grammar and semiotic constraints. In M. Christiansen & S. Kirby (Eds.), *Language Evolution* (pp. 111–139). New York: Oxford University Press.

Shannon, C. & Weaver, W. (1949). *The Mathematical Theory of Communication.* Urbana: University of Illinois Press.

Maxwell, J. C. (1867). On the Dynamical Theory of Gases. *Philosophical Transactions of the Royal Society* 157, 49–88.

Polanyi, M. (1968). Life's irreducible structure. *Science* 160, 1308–1312.