Information and Reference

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Abstract The technical concept of information developed after Shannon [22] has fueled advances in many fields, but its quantitative precision and its breadth of application have come at a cost. Its formal abstraction from issues of reference and significance has reduced its usefulness in fields such as biology, cognitive neuroscience and the social sciences where such issues are most relevant. I argue that explaining these nonintrinsic properties requires focusing on the physical properties of the information medium with respect to those of its physical context—and specifically the relationship between the thermodynamic and information entropies of each. Reference is shown to be a function of the thermodynamic openness of the information medium. Interactions between an informing medium and its physical context that drive the medium to a less probable state create intrinsic constraints that indirectly reflect the form of this extrinsic influence. This susceptibility of an informing medium to the effects of physical work is also relevant for assessing the significance or usefulness of information. Significance can be measured in terms of work "saved" due to access to information about certain contextual factors relevant to achieving a preferred target condition.

1 Introduction

> *I didn't like the term Information Theory. Claude didn't like it either. You see, the term 'information theory' suggests that it is a theory about information – but it's not. It's the transmission of information, not information. Lots of people just didn't understand this… information is always about something. It is information provided by something, about something. (Interview with R. Fano, 2001)*

> *What I have tried to do is to turn information theory upside down to make what the engineers call "redundancy" [coding syntax] but I call "pattern" into the primary phenomenon… (Gregory Bateson, letter to John Lilly on his dolphin research, 10/05/1968)*

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In common use and in its etymology the term “information” has always been associated with concepts of reference and significance—that is to say it is *about* something for some *use*. But following the landmark paper by Claude Shannon [22] (and later developments by Wiener, Kolmogorov and others), the technical use of the term became almost entirely restricted to refer to signal properties of a communication medium irrespective of reference or use. In the introduction to this seminal report, Shannon points out that, although communications often have meaning, “These semantic aspects of communication are irrelevant to the engineering problem,” which is to provide a precise engineering tool to assess the computational and physical demands of the transmission, storage and encryption of communications in all forms.

The theory provided a way to precisely measure these properties as well as to determine limits on compression, encryption and error correction. By a sort of metonymic shorthand this quantity (measured in bits) came to be considered synonymous with the meaning of “information” (both in the technical literature and in colloquial use in the IT world) but at the cost of inconsistency with its most distinctive defining attributes.

This definition was, however, consistent with a tacit metaphysical principle assumed in the contemporary natural sciences: the assertion that only material and energetic properties can be assigned causal power and that appeals to teleological explanations are illegitimate. This methodological framework recognizes that teleological explanations merely assign a locus of cause but fail to provide any mechanism, and so they effectively mark a point where explanation ceases. But this stance does not also entail a denial of the reality of teleological forms of causality nor does it require that they can be entirely reduced to intrinsic material and energetic properties.

Reference and significance are both implicitly teleological concepts in the sense that they require an interpretive context (i.e. a point of view) and are not intrinsic to any specific physical substrate (e.g. in the way that mass and charge are). By abstracting the technical definition of information away from these extrinsic properties, Shannon provided a concept of information that could be used to measure a formal property that is inherent in all physical phenomena: their organization. Because of its minimalism, this conception of information became a precise and widely applicable analytic tool that has fueled advances in many fields, from fundamental physics to genetics to computation. But this strength has also undermined its usefulness in fields distinguished by the need to explain the non-intrinsic properties associated with information. This has limited its value for organismal biology, where function is fundamental, for the cognitive sciences, where representation is a central issue, and for the social sciences, where normative assessment seems unavoidable. So this technical redefinition of information has been both a virtue and a limitation.

The central goal of this essay is to demonstrate that the previously set aside (and presumed nonphysical) properties of reference and significance (i.e. normativity) can be reincorporated into a rigorous formal analysis of information that is suitable for use in both the physical (e.g. quantum theory, cosmology, computation theory) and semiotic sciences (e.g. biology, cognitive science, economics). This analysis builds on Shannon's formalization of information but extends it to explicitly model its link to the statistical and thermodynamic properties of its physical context and to the physical work of interpreting it. It is argued that an accurate analysis of the nonintrinsic attributes that distinguish information from mere physical differences is not only feasible, but necessary to account for its distinctive form of causal efficacy.

Initial qualitative and conceptual steps toward this augmentation of information theory have been outlined in a number of my recent works [8–12]. In these studies we hypothesize that both a determination of reference and a measure of significance or functional value can be formulated in terms of how the extrinsic physical modification of an information-bearing medium affects the dynamics of an interpreting system that exhibits intrinsically end-directed and self-preserving properties.

2 Background

The problems posed by the concepts of reference and significance have been the subject of considerable philosophical debate over many centuries. It would probably not be hyperbole to suggest that they are among the most subtle and complex issues in the history of philosophy. So it might seem presumptuous to imagine that these questions can be settled with a modest extension of formal information theory. Though it is often assumed that the current technical treatment of information either resolves these issues or shows them to be irrelevant, the fact that concepts of meaning and interpretation are treated as irrelevant to physical science and in biology indicates that a major gap in understanding still separates these technical uses from the traditional meaning of the term. Though it is not possible to even come close to doing justice to this long and byzantine philosophical history of analysis in this essay, it is worth setting the stage with a fundamental insight gleaned from this perspective.

The challenge posed by these ideas was eloquently, if enigmatically, formulated by Franz Brentano's [4] use of the terms "intention" and "inexistence" (borrowed from Medieval philosophy) when describing the referential property of information.

> Every mental phenomenon is characterized by what the Scholastics of the Middle Ages called the intentional (or mental) inexistence of an object, and what we might call, though not wholly unambiguously, reference to a content, direction toward an object (which is not to be understood here as meaning a thing), or immanent objectivity

… Brentano's use of the curious term "inexistence" points to the fact that informational content is not exactly an intrinsic physical property of the medium that conveys it, even though it somehow inheres in it as well. The reference conveyed is typically displaced, abstract, ambiguous, or possibly about something nonexistent. And in any case it is dependent on interpretation. Excluding this attribute from the technical concept of information appears to have been necessary to ground information theory in physics and make it suitable for engineering applications, but *this was bought at a cost of ignoring the very attributes that distinguish information from other physical phenomena*.

I argue that the key to formulating a more adequate concept of information that includes these "inexistent" properties is to be found, ironically, in more carefully attending to the physicality of information media. A hint that this is important is captured in two distinctively different uses of the concept of entropy (informational entropy and thermodynamic entropy). The term "entropy" was, of course, originally coined by Rudolph Clausius in [7] in the context of the early development of a concept of the relationship between heat and physical work. In 1874 Ludwig Boltzmann [3] formalized it further in his H-theorem that represents entropy in terms of the sum of the probabilities of microstates of a dynamical system. In Shannon's [22] analysis (building on the work of his predecessors at Bell Labs, Nyquist and Hartley), this same formula is used to represent the information of a given communication medium, also describing its distinguishable states. Apparently, following a suggestion from the mathematician John von Neumann, he also called this value "entropy". Many writers have cogently argued that these two concepts should not be confused (e.g. [15, 20, 24, 26]), and that Shannon's choice of this term to describe a statistical property of information media was a colossal mistake (e.g. [25]). And there is, of course, much to distinguish these two uses of the same term beyond this abstract mathematical similarity. For example, there is no informational analogue to Clausius' theorem that the total entropy of an isolated physical system can only increase (the second law of thermodynamics). Nor is informational entropy a dynamical concept associated with energy and work. Nevertheless, many have attempted to discern a deeper linkage underlying these statistical analogies (e.g. [2, 14, 21]).

The idea that there is a link between information and thermodynamics has a long history. Ways of demonstrating such a linkage have been proposed in many forms from Maxwell's [19] famous demon [18] to Landauer's [17] argument about the thermodynamic cost of information erasure. However, these approaches focus primarily on the energetic and thermodynamic "costs" of manipulating physical markers or taking measurements and how this might alter system entropy. So they have largely ignored the problem of how reference and significance are physically instantiated, to instead defend the belief that information cannot be used to violate the second law of thermodynamics.

Both notions of entropy can be applied to physical features of an information medium. This is because any physical medium capable of conveying information must be able to exhibit different states. As Shannon demonstrated, the number and relative probabilities of these different states (and, in a continuous communication, their rates of change) are what determines the capacity for that medium to "store" or "convey" information. Following insights from statistical mechanics, he argued that this could be measured in terms of the value of $-\sum p_i \log p_i$, where p_i is the probability of the occurrence of a given state i of the information-bearing medium. Any process, structure, or system that can be analyzed onto component states, each able to be assigned a probability of being exhibited, can in this way be described in terms of this measure of information. This insight at the foundation of Shannon's approach also provided one of the first widely accepted model-independent measures of complexity [11]. Most subsequent means of measuring form or complexity have been developed with respect to this basic insight (as in the work of [6, 16], etc.). Information theory thus became more than just a tool for analyzing communication.

Besides providing a measure of the information capacity of a given medium, Shannon's analysis also demonstrated that the amount of information provided by a *received* signal (i.e. a message) can be measured as a function of the amount of uncertainty that the received signal removes. This can be measured as a difference between the prior (or intrinsic) uncertainty (the Shannon entropy) of the signal medium being in a given state and its current received state (e.g. in a received message). This necessarily relational nature of information is an important distinction that is often overlooked, and it effectively distinguishes two interdependent and inter-defined uses of the concept: the potential information capacity of a given medium and the information provided by a specific message conveyed by that medium. Both states can be assigned an entropy value. Using this relative measure, problems of noise, error correction and encryption can be likewise analyzed in terms of differences or changes in component signal state probabilities.

The relational nature of information, even in this technically minimalistic form, is an important clue to the fact that information is not a simple intrinsic property of things. Interestingly, this is also a feature that both concepts of entropy share. The third law of thermodynamics likewise asserts that entropy is a relational measure: a difference between states of a system. The relational nature of thermodynamic entropy was not fully appreciated until 1906 when Walter Nernst augmented thermodynamic theory establishing an absolute reference point at 0° K. Likewise the relational nature of informational entropy is also often overlooked.

The entropy of a signal is also not an intrinsic property but a relational property. This relational character of both concepts of entropy is a clue that the statistical signal properties of a medium are linked to its ability to convey reference. Both Shannon's analysis and thermodynamic theory depend on comparing the relative degree of constraint on current entropy with respect to what is minimally and/or maximally possible for a given system. A received signal that exhibits constraint in its information entropy is more predictable even if it is not reduced to a single fixed value. Thus even a noisy signal reduces uncertainty by this difference, so long as it is not fully random.

Noise, which is the corruption of a signal, increases uncertainty by reducing this constraint. But noise is often the result of physical degradation of the conveying medium. This is yet a further clue to the intrinsic interrelationship between thermodynamic and information entropy.

The distinction between signal and noise is an important clue to how an information-bearing medium can be linked to some nonintrinsic object, event, or property. Noise is a difference or change of the information entropy of a message. Often, as in the case of radio transmission, noise is due to an increase in thermodynamic entropy of the conveying medium as a result of interference or simple signal degradation, i.e. to factors extrinsic to the information-bearing medium that affect its physical attributes. Any such physical influence will entail physical work, and work entails a change in thermodynamic entropy. This suggests that what at first appears to be an unrelated and superficial parallelism between these two concepts of entropy is instead a critical clue to how a signal medium can be about something that it is not.

Noise and signal are *both* linked to something extrinsic that has affected the information medium. The difference is due to interpretive assessment, not anything intrinsic to the informing medium. The nonintrinsic distinction between signal and noise is an additional relational attribute indicating that, even though specific reference and significance can be set aside to analyze the statistical properties of an information-bearing signal, they are nevertheless assumed.

3 Physicality of Aboutness

To exemplify the way that the statistical properties of a medium can provide the potential for reference, consider the use of information-theoretic analyses in molecular biology. The statistical properties of nucleotide sequences can provide critical clues to potential biological functions even though the sequencing of genomes is largely accomplished in ignorance of any specific gene function. Indeed, exploring the statistical structure of these sequences has provided many important clues to unanticipated functional properties of DNA, RNA and the organic properties they specify. For example, the presence of constraints on the possible statistical entropy of a gene sequence, exhibited in sequence redundancy across species, tends to predict that the sequence in question plays a functional role in the organism, i.e. that it encodes information “about” that function. This is because constraint in the form of redundancy provides evidence that nonrandom—i.e. functional—influences are at work. Simply scanning gene sequences for constraint, then, provides a tool for discovering sequences that probably contain information “about” some function, even though no specific functional information is provided.

The concept of mutual information is also a clue to the way that signal constraint relates to reference. The mutual information between two signals or sequences of alphanumeric characters is a measure of their statistical nondifference. This can even be assessed despite nonidentity of any of the components in the two, as for example exists in the statistical parallels between nucleotide sequences in DNA and amino acid sequences in proteins. Shannon demonstrated that any degree of signal noise less than total noise can be compensated for by a comparable level of signal redundancy. In this respect, redundancy—a constraint on possible variety—is what preserves signal reference. In genetic evolution, sequence redundancy and mutual information are clues that a given genetic signal carries functional information and provides a kind of reference to cellular-molecular dynamics that were useful in the past and are likely useful in the present. As the epigraph to this essay from Gregory

Bateson suggests, reference is ultimately embodied in signal constraint (i.e. redundancy and the regularity or pattern that this produces).

So implicit in the technical sense of "information" is an understanding that statistical properties of the signal medium are in some way related to its referential function. The question that I want to address is how it might be possible to more precisely characterize this relationship.

To address this let us begin with a focus on the relationship between thermodynamic and information entropy. Worries about the relationship between information and thermodynamics emerged in parallel with the kinetic theory of gasses and long predate Shannon's use of the entropy concept. They are best exemplified by the many analyses that developed in response to Maxwell's [19] famous thought experiment, which subsequently came to be known as Maxwell's demon. Though he was one of the major contributors to the formalization of the second law of thermodynamics, Maxwell pondered the possibility that molecular-level information might be able to drive an otherwise isolated thermodynamic system from a higher to a lower entropy state in violation of the second law. He described this problem in terms of a fanciful microscopic "demon" able to judge the relative momentum and/or velocity of gas molecules in either side of a two-chambered container with a closable passage separating them. He wondered whether the demon could use these measurements to determine whether or not to let a molecule move from one container to the other. Such a demon (or a device that acted in the same way) could selectively allow only fast-moving molecules to pass one way and only slow-moving molecules to pass the other way, thus progressively reducing the entropy of the whole system, in violation of the second law. But if this were even logically conceivable (even if not achievable with any physical mechanism), then the ubiquity and ineluctable directionality of the second law would be questioned.

Subsequent analysts have variously attempted to answer this conceptual challenge and preserve the second law by analyzing the thermodynamic aspects of the information assessment process. This has been explored in simplified abstract mechanical terms involving one or just a few moving particles (e.g. [23]), or by considering the relative entropic "cost" of acquiring this information (e.g. [5]), or in terms of the need to erase information from previous measurements in order to repeat the process (e.g. [17]). The intention has been to show that, even if one were able to create a device capable of such actions, the second law of thermodynamics would be preserved because there would be more entropy generated by obtaining and using this information than would be reduced by its actions.

In contrast, I propose to analyze the referential property of information directly and irrespective of the energetic cost of generating or erasing bits of data (though ultimately this cost is a relevant factor as well). For this purpose I instead focus on one of the most basic principles of Shannon's analysis: the role played by statistical constraint in the assessment of the amount of uncertainty removed by receipt of a given message or introduced by thermodynamic noise in a transmission. This allows us to make an abstract, but direct, comparison between the entropy of a given information-bearing medium in Shannon's terms and the entropy of that same medium in physical terms (though not necessarily just in thermodynamic terms).

The unifying factor is that both are expressions of the physical attributes of the information-bearing medium.

The essential point is this: every medium for storing or conveying information is constituted physically and its distinguishable states are physical states. So any change in that medium's statistical physical properties (e.g. its thermodynamic entropy) could potentially also change its informational properties. This is not a necessary relationship, since the distinguishable states used to convey information in any given case are inevitably a very small subset of the total range of different states that the physical medium can assume. However, because of its physicality, any change in the informational entropy of a given medium must necessarily also entail a change in its physical statistical properties. And, following the strictures of the second law of thermodynamics, any physical medium will only tend to be in an improbable constrained state if it has in some way been driven away from its more probable state by the imposition of physical work or prevented from achieving it by some extrinsic restriction. In other words, the relationship between the most probable state of the medium and the observed state at any particular moment is a reflection of its relationship with its physical context. Its intrinsic statistical properties are therefore clues to factors that are extrinsic to it.

In this analysis I build on this insight to argue that *referential* information is based on the constraints generated by physical work introduced due to the thermodynamic openness of an information-bearing medium and its susceptibility to contextual modification. The next section provides a point-by-point outline of the logic that formally defines the referential aspect of information in terms of the relationship between Shannon (information) entropy and Boltzmann (thermodynamic) entropy.

4 Steps to a Formalization of Reference

A. General case: passive information medium near equilibrium (e.g. geological formation, crime scene evidence, data from a scientific experiment, text, etc.)

1. Information (e.g. Shannon) entropy is not equivalent to thermodynamic (e.g. Boltzmann–Gibbs) entropy (or to the absolute statistical variety of physical states). [For convenience these entropies will be provisionally distinguished as Shannon vs. Boltzmann entropy, though recognizing that each includes multiple variant forms.]
2. However, for any physical signal medium, a change in Shannon entropy must also correspond to a change in Boltzmann entropy, though not vice versa because the distinctions selected/discerned to constitute the Shannon entropy of a given signal medium are typically a small subset of the possible physical variety of states—e.g. statistical entropy—of that medium.

3a. The Shannon information of a received message is measured as a reduction of signal uncertainty (= a reduction of Shannon entropy).

3b. For a simple physical medium, reduction of Shannon entropy must also correspond to a reduction of the Boltzmann entropy of that medium.
3c. This can be generalized as “any deviation away from a more probable state” (which can violate 3b in the case of media that are actively maintained in an improbable state, such as maintained far from equilibrium). (**See B below**.)
4a. A reduction of Boltzmann entropy of any physical medium is exhibited as constraint on its possible states or dynamical “trajectories”.
4b. The production of physical constraint requires physical work in order to produce a decrease of Boltzmann entropy, according to the second law of thermodynamics.
5a. For a *passive medium* the physical work required to reduce its Boltzmann entropy must originate from some physical source *extrinsic* to that medium.
5b. Generalization: Constraint of the Shannon entropy of a passive medium = constraint of its Boltzmann entropy = the imposition of prior work from an external source.

6. An increase in constraint (i.e. deviation away from a more probable state) in the information medium literally “re-presents” the physical relationship between the medium and the extrinsic contextual factors (work) that caused this change in entropy (= what the information embodied in the constraint can be “about”).
7. Since a given constraint has statistical structure, its *form* is a consequence of the specific structure of the work that produced it, the physical susceptibilities of the information-bearing medium and the possible/probable physical interactions between that medium and this extrinsic contextual factor.
8. The form of this medium constraint therefore corresponds to and can indirectly “re-present” the *form* of this work (i.e. in-*form*-ation).
9. Conclusion 1. The possibility of reference in a passive medium is a direct reflection of the possibility of a change in the Boltzmann and Shannon entropies of that medium due to a physical interaction between the information-bearing medium and a condition extrinsic to it.
10. Conclusion 2. The possible range of contents thereby referred to is conveyed by the form of the constraint produced in the medium by virtue of the form of work imposed from an extrinsic physical interaction.
11. Conclusion 3. The informing power of a given medium is a direct correlate of its capacity to exhibit the effects of physical work with respect to some extrinsic factor.
12. Corollary 1. What might be described as the referential entropy of a given medium is a function of the possible independent dimensions of kinds of extrinsically induced physical modifications it can undergo (e.g. physical deformation, electromagnetic modification, etc.) multiplied by the possible “distinguishable” states within each of these dimensions.

13. Corollary 2. Having the potential to exhibit the effects of work with respect to some extrinsic physical factor means that even no change in medium entropy or being in a most probable state still can provide reference (e.g. the burglar alarm that has not been tripped, or the failure of an experimental intervention to make a difference). It is thus reference to the fact that *no work to change the signal medium has occurred.*

In addition, since not all information-bearing media are inert physical structures or otherwise passive systems at or near thermodynamic equilibrium, we need to modify certain of these claims to extend this analysis to media that are themselves dynamical systems maintained far from equilibrium. This yields the following additional claims:

B. Special case: nonpassive information medium maintained far from equilibrium (e.g. metal detector or organism sense organ)
1. A persistently far-from-equilibrium process is one that is maintained in a lowered probability state. So certain of the above principles will be reversed in these conditions, specifically, those that depend on extrinsic work moving a medium to a lower probability, lower entropy state.
2. Maintenance of a low Boltzmann entropy dynamical process necessarily requires persistent physical work or persistent constraints preventing an increase of Boltzmann and Shannon entropies.
3. Any corresponding increase in Shannon entropy therefore corresponds to a disruption of the work that is maintaining the medium in its lower entropy state. This can occur by impeding the intrinsic work or disrupting some dissipation-inhibiting constraint being maintained in that system.
4a. An increase in the Shannon entropy of a persistently far-from-equilibrium information medium can thereby “indicate” extrinsic interference with that work or constraint maintenance.
4b. A persistently far-from-equilibrium dynamical medium can be perturbed in a way that increases its entropy due to contact with a passive extrinsic factor. Any passive or dynamic influence that produces a loss of constraint in such a system can provide reference to that extrinsic factor.
5a. Since work requires specific constraints and specific energetic and material resources, these become dimensions with respect to which the change in entropy can refer to some external factor.
5b. The dynamical and physical properties of a far-from-equilibrium information-bearing medium determine its “referential entropy”.
6. Corollary 3. This can be generalized to also describe the referential capacity of any medium normally subject to regular end-directed influences that tend to cause it to be in an improbable or highly constrained state. This therefore is applicable to living systems with respect to their adaptations to avoid degradation and also to far more complex social and cultural contexts where there is active “work” to maintain certain “preferred” orders.

5 Active Acquisition of Information

The far-from-equilibrium case is of major importance also because it provides the foundation for an analysis of the nature of an interpretive process, such as might be applied to simple organism adaptations and genetics (see next section).

A simple exemplar of a far-from-equilibrium information medium is a metal detector. Metal detectors typically operate by constantly maintaining a stable electromagnetic field. This signal medium requires the work provided by the constant flow of an electric current through a coil. This magnetic field is easily distorted by the presence of a conducting object, thus interfering with the electronic work otherwise maintaining a redundant signal also linked to this work (often the tone produced by an oscillator sensitive to a change in current).

This is roughly analogous to the way that living processes gain information about their world. Whether by virtue of a ligand binding to a specific receptor molecule on a cell surface and changing its conformation or a photon modifying the dynamics of signal processing in retinal neurons, it is ultimately interference with an ongoing living process requiring metabolic work that provides referential information to an organism.

Recall that, according to Shannon's analysis, the measure of information in a message is proportional to the reduction of entropy in the received signal compared with the potential entropy of the channel (i.e. the medium). Now we can see that reduction of the Boltzmann entropy ($-\Delta S_b$) of the passive information medium is proportional to a reduction of its Shannon entropy ($-\Delta S_s$) by some proportionality constant m (usually far below 1.0) that determines what portion of its Boltzmann entropy is used as Shannon entropy. In the far-from-equilibrium case the situation is reversed: some fraction of the increase in a medium's Boltzmann entropy ($+\Delta S_b$) is proportional to an increase of its Shannon entropy ($+\Delta S_s$). In both cases, information about the source of an external disturbance is negatively embodied in the Shannon entropy ($\pm\Delta S_s$) of the medium as a change in intrinsic constraint.

In general this means that a medium in its most probable state, exhibiting no change in entropy, can also provide information about the *absence* of a given specific referent. This is nevertheless a form of reference. A smoke alarm that remains silent in the absence of smoke still provides information. So both a high probability state and a low probability state of an information medium are potentially referential, demonstrating that every referential relationship corresponds to a reduced probability state of Shannon entropy. Thus we can conclude that reference is made possible by the susceptibility of a given information medium to reflect the effect of work with respect to an extrinsic context, and that the sign of this effect—i.e. whether there is an increase or decrease of medium constraint—will depend on whether this work originates in the interpretive process or in its extrinsic physical context.

6 Conclusion

The above analysis demonstrates that the capacity of an informing medium to provide reference (i.e. "aboutness") derives from a linkage between its information entropy and thermodynamic entropy. Despite the fact that these are nonequivalent statistical measures of different properties (e.g. free energy vs. formal complexity, respectively) they can both reflect related changes introduced by physical work. So although reference is not an intrinsic physical property of any information-bearing medium, this linkage to work renders the referential property of information susceptible to exact formal and empirical analysis. Thus reference is not a subjective, heuristic, or epiphenomenal product of prescientific theorizing, like phlogiston, able to be dispensed with as more precise physical science comes to explain it away. Rather, it is a causally relevant physical property affecting systems that depend on selected contextual features for their operation, but lack direct access to them.

This qualitative analysis does not provide a way to quantify something like referential capacity. Indeed, it is not clear what such a measure might consist in. But it does suggest that to utilize the state of a mediating substrate to access the reference afforded by that medium's intrinsic constraints, an interpreting system must do so with respect to the consequences of work. For such a system, functional significance can be assigned to this referential information with respect to work "saved" due to access to information about contextual factors relevant to achieving a preferred target condition. This implies that a system capable of assessing reference must be organized to achieve or maintain a far-from-equilibrium state, such as in a living system.

Although the qualitative form of this analysis may still limit technical applications, such as in molecular biology, cognitive neuroscience, or artificial intelligence, it should nevertheless be sufficient to serve as a framework for the future development of a precise formal theory of reference and functional significance.

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