Information Theory as a General Language for Functional Systems

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Abstract. Function refers to a broad family of concepts of varying abstractness and range of application, from a many-one mathematical relation of great generality to, for example, highly specialized roles of designed elements in complex machines such as degaussing in a television set, or contributory processes to control mechanisms in complex metabolic pathways, such as the inhibitory function of the appropriate part of the lac-operon on the production of lactase through its action on the genome in the absence of lactose. We would like a language broad enough, neutral enough, but yet powerful enough to cover all such cases, and at the same time to give a framework form explanation both of the family resemblances and differences. General logic and mathematics are too abstract, but more importantly, too broad, whereas other discourses of function, such as the biological and teleological contexts, are too narrow. Information is especially suited since it is mathematically grounded, but also has a well-known physical interpretation through the Schrödinger/Brillouin Negentropy Principle of Information, and an engineering or design interpretation through Shannon's communication theory. My main focus will be on the functions of autonomous anticipatory systems, but I will try to demonstrate both the connections between this notion of function and the others, especially to dynamical systems with a physical interpretation on the one side and intentional systems on the other. The former are based in concepts like force, energy and work, while the latter involve notions like representation, control and purpose, traditionally, at least in Modern times, on opposite sides of the Cartesian divide. In principle, information can be reduced to energy, but it has the advantage of being more flexible, and easier to apply to higher level phenomena.

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1. INTRODUCTION

Energy underlies all physical activity, as George Farre argues in this conference. This general position, when extended to all phenomena is a special form of naturalism that might be called dynamical realism. It can be characterized as the view that everything that can be understood can be understood in principle as a manifestation of dynamical properties, i.e., relations of forces, flows and energies. Whether dynamical realism is regarded as an ideology, research program or methodology, its success will depend heavily on how well it can deal with teleological properties like function. Some of the specifics of the ideas in this paper are illustrated in the paper by my colleagues Wayne Christensen and Cliff Hooker, and others by that of Alexei Sharov. I will concentrate on fairly abstract ideas to develop a metaphysics of function. This implies a common language for representing central aspects of function and its related concepts. I will argue that contemporary information theory, if applied with appropriate finesse, is suitable. By this I mean that functional theory is not a consequence of information theory, but that appropriate structures can be defined within information theory that capture central ideas of function. Uses range from highly specialized roles of designed elements in complex machines such as degaussing in a television set, or contributory processes to control mechanisms in complex metabolic pathways, such as the inhibitory function of the appropriate part of the lac-operon on the production of lactase through its action on the genome in the absence of lactose. Ideally, we would like to have some language broad enough, neutral enough, but yet powerful enough to cover all such cases, and at the same time to give a framework form explanation both of the family resemblances and differences. I believe that the language of contemporary information theory is nearing a stage in which it is suitable for this task. I am not a mathematician, and if I tried to do this formally, I would probably do it badly. What I will do instead is to sketch what is required.

General logic and mathematics are too abstract, but more importantly, too broad, whereas other discourses of function, such as the biological and teleological contexts, are too narrow. Information is especially suited since it is mathematically grounded, but also has a well-known physical interpretation through the Schrödinger/Brillouin Negentropy Principle of Information, and an engineering or design interpretation through Shannon's communication theory. In the last few years these approaches have been mathematically related, and though there are some remaining difficulties, we are close to a unified information theory. Recent work in information theoretic semantics, though also not without its problems, promises to extend this unification into the intentional and mental realm.

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2. TYPES OF FUNCTION

There are some senses of ‘function’ that are easy to reconcile with dynamical realism, notably the mathematical notion and mechanical notions used in engineering. However, function can range in normal use from abstract mathematical function, a mapping from ordered sets of parameters each to a unique value to function in biological and social settings. A special case important in general systems theory restricts the parameters to the inputs and the values to the outputs. The system laws or rules embody a mathematical function. A system model is an abstract “black box”, that is an abstraction from the actual embodiment of the system. Interestingly, Fisherian selection theory is an example of this sort of model, as is Skinnerian behaviorism. Further restrictions concern regularities in inputs and outputs, in which the former are called source laws and the latter are called consequence laws.

More restrictions arise when we consider the requirement that any system must be dynamically embodied. That is, any system must satisfy the laws of nature governing forces and flows. Example laws at a fundamental level are Newton’s second law, quantum mechanics and the Second Law of thermodynamics, which governs energy in its guise as work capacity and entropy flows. There are large numbers of dynamical laws at higher levels, including, e.g., Mendel’s Laws and various psychophysical laws. We call the view that all real properties are based in dynamical properties dynamical realism.
These restrictions apply to any dynamical system, i.e., the constraints are necessary for the reality of the system. Dynamical realism implies these constraints are also sufficient for the reality of the system. So far, nothing requires the anticipate character of the function (contrary to, e.g. Richard Dawkins, and B.F. Skinner). This suggest that at base, anticipation is a dynamical issue. I suggest that this is supported by the observation that anticipation requires a flow of information from downstream consequences to system regulation (laws) to downstream modulation of system responses, resulting in a change of consequences (for further details, see the related papers by Christensen and Hooker\textsuperscript{1} and Alexei Sharov\textsuperscript{13}. In designed systems and self-regulatory systems the flow from the downstream consequences may be either through another system designed to control the base system, or through higher ordered anticipated consequences (further detail is in a joint paper by the Newcastle Group\textsuperscript{3}). Donald Campbell calls such higher order control “vicarious selection”, but I find the term misleading, since it suppresses the overall organisational nature of control in anticipatory systems. Vicarious selection is no doubt an important concept, but it has the same problems as other black box models.

Anticipation and regulation, then, involve information flows. On the mathematician’s notion of dynamics, in which anything involving a V or a dx is dynamical, this observation is enough to render anticipation dynamical, but it is not enough for dynamical realism. Information is widely regarded as abstract, whereas physical dynamics are concrete. Obviously, restrictions need to be placed on the concept of information to tie it down to earth. I will address this shortly.

### 3. THE PHYSICAL BASIS OF ANTICIPATORY FUNCTION

There are at least two reasons to think that function in the sense of biological or mechanical anticipatory function is not physical (at least in the usual sense of physics), even if we ignore antiquated vitalist and teleological views of causation descending from the Aristotelian world view. In other words, there are reasons even within the Modern perspective to suspect that function is fundamentally unlike the mechanical physics that heralded the modern era. Similar arguments carry over to mental functions.

First, Elliot Sober\textsuperscript{14} has argued that although fitness, a product of function and environment, and the consequence of adaptation, is supervenient on the physical but is not itself physical, since the same biological (for Fodor, mental) function can be realized physically in many different ways, with no common physical character. Thus the particular physical form is of little importance, and the biological (mental) organization is both explanatorily and ontologically more important. I have argued that supervenience is of little explanatory value\textsuperscript{3}. Note for example that the motions of billiard balls are the same whether they are made of plastic or ivory, as long as they have the same mass and size. Yet that their motion is supervenient on their composition is of little consequence, if any.

Second, as I have pointed out\textsuperscript{3} biological (and mental) traits are often multipurpose, so a functional decomposition need not correspond with any obvious physical decomposition. For example, in an airplane the lift and thrust functions are located in separate modules, as is common in human designed artifacts, which are generally put together from the bottom up with specific goals in mind. In a bird, bat, or flying insect, however, the lift and thrust functions are found in the same physical structure, the wing, and separating the functions on the basis of physical structure is difficult if not impossible. It is typical of natural functions that they make use of whatever resources available in a holistic and outcome oriented way. This seems to prevent reduction, which in turn makes a physical analysis of the sort applied by early Modern scientists to previous intractable domains like the Heavens dubious.

I will argue that the resolution of these problems requires a non-reductive physicalism in the form of dynamical realism allowing emergent properties, entities and laws, but that retains an explanatory unification through common principles operating at a variety of levels Collier and Burch, in press), and ontological modesty in the number of basic kinds required. Particular systems may introduce new particular irreducible properties, but once we properly understand the difference between constitution and reduction, most objections dissolve. The apparent problems stem from a false assumption that logical and physical composition and analysis go hand in hand, whereas a study of the properties of emergent hierarchies shows that this is sometimes, nay almost always, not the case.
First, though, some discussion of goals will be useful. The clearest sense involves an explicit representation of the goal, and selection of a means to reach the goal, followed by implementation of these means and eventual success or failure in reaching the goal. At the other end of the scale of directedness we have telematic function. In this case the goal is not explicitly represented, and there is no intentional selection of means, nor is there any guarantee that success will reinforce the success of the telematic system. In contrast, and someplace between teleological and teleomatic functions, are teleonic functions, in which success at achieving the goal reinforces the success of the system that has those ends (and may incidentally reinforce its means as well).

In teleonic systems, the chain of supported success must stop someplace; the obvious place to stop is the overall viability of the system. This provides a natural definition of teleonomy in naturalistic terms: a function is teleonic if and only if success in achieving its ends contributes to the viability of the system.

Unlike teleonic systems, which receive their goals from external factors, and then proceed more or less independently towards those ends, teleonic systems are more than merely independent; they show a certain degree of autonomy in the sense that they determine their own goals through the particular circumstances of their own viability conditions. More advanced teleonic systems can modify their functions so as to try to enhance their viability. Typically, the viability envelope for living systems is continually changing, partly because living systems have the relatively shallow energy wells typical of self-organised systems, and depend on complex organisation to maintain themselves against external and internal threats. This emphasis on organisation makes informational accounts central.

Complex functional organisation is inherently hierarchial, but this allows various levels to work against each other. Cell preservation, for example, is usually subordinate to organism preservation, but this may fail in cancer. Similarly, organism preservation is usually subordinate to organism lineage preservation, but this can also go astray. More generally, there is a hierarchy of competing ends, each capable, under some circumstances, of over-riding others.

This is especially evident when teleological ends come into play in systems with cognitive and moral capacities. Moral ends can over-ride self-preservation. Similarly, Kierkegaard speaks of teleological suspension of the ethical. Nonetheless, the primary function of cognition is preservation of self and lineage, so at least in natural biological systems, teleology is grounded in telonomy.

I would no like to return briefly to the objections raised at the beginning of this section. As to the multiple realisations of the same function, the same thing happens with billiard balls, so the argument does not establish its conclusion. More importantly, and as will be made more clear in the next section, the dynamical basis of function is not subject to multiple realisations when the physical organisation that produces the function is understood as a system at the right level. Similar arguments mitigate the problem of the apparent discrepancy between functional and structural decomposition. Correct attention to organisational factors according to the principles of dynamical realism helps to identify the correct structures that manifest functions. Also, the holistic nature of teleonomy suggests that many apparently different functions are really part of the basic function of self-preservation.

4. INFORMATION AND ITS CONSEQUENCES

We can distinguish organisation from mere complexity through larger scale (higher order) correlations (redundancies) that correspond to cohesion, structural or process closure. Within organisation, we can distinguish function via its downstream modulation of information and energy flows in the system, and also between the system and its environment. Redundancies are best understood in terms of information theory. The problem is to give them a physical basis. Information has two meanings in the dictionary, one is representational and intentional. But the other refers to raw, uninterpreted data. This is the usage I will depend for the quantification of form.

Later, I will use a dynamical information theory to tie the language of control and function to that of energy, force and work, and I will argue that autonomous agents thrive best in a regime with relatively gentle selection and the encouragement of variety. This is best achieved through the cultivation of adaptability rather than simple adaptedness. This is simply a version of the rubric that it is better to teach a person to learn than to teach them a specific trade.
First, though, I will introduce a simple model of information based in logic, and briefly indicate the current state of its technical development, but my main concern is to introduce the fundamental information theoretic notion of a distinction, which is neutral between abstract and concrete interpretation. Before I can do this, though, I must develop a general paradigm of explanation in terms of form, a paradigm that is becoming increasingly popular with the recognition that analytical methods fail for even moderately complex systems. The notion of a distinction can be used for the quantification of the form of something, so that form can be treated on a par with other mathematical properties. This can be done by mapping the form of something onto a string of bits isomorphically by answering yes and no questions until there are no more distinctions to be made, so that all structure in the form is represented in the string, and then the complexity of the string is determined by its maximally compressed form (see Figure 1).

![Figure 1. Compression of form into a binary string](Image)

The usual way to do this is to use algorithmic information theory, but that is plagued with some technical problems involving computational overhead. I will assume that these can be resolved eventually, e.g., by requiring a reference machine for all such computations that minimises the computational overhead. Interestingly, the compressed form produces all and only truth table rows that fir the object. It has the basic dimensionality of the complexity of the object, and corresponds to what is called a generator, since it generates everything that is intrinsically true of the object. The idea was introduced by Wittgenstein in the *Tractatus*.

In order to give a physical interpretation of these compressed strings, which numerically give the and represent the form of their original source, I argue that causation can be interpreted in terms of the transfer of information under the assumption of Schrödinger’ Negentropy Principle of Information, according to which the information is the complement of the entropy of some entity. This allows a rigorous and quantitative definition of causation as the propagation of and transformation of form that applies readily both to classical physics and contemporary quantum mechanics, as well as more loosely to ideas like d’ArcyThompson’ s and more recent ideas concerning causal processes as the non-computable transformation of patterns in self-organizing systems and other systems with strange attractors’.

### 5. COMPLEXITY AND ORGANISATION

The next step is to constrain the notions of function and control within this physical theory, and show how the result is amenable to the study of organization in both hierarchies and heterarchies. Through the notion of teleonomy as functionally organized self-maintenance, these ideas can be used to explain autonomy, and to show how all other function is grounded in autonomy.

We can distinguish organisation from mere complexity through larger scale (higher order) correlations (redundancies) that correspond to cohesion (structural and process closure contributing to identity. The highest order contributing to viability represents autonomy. Cohesion is a central notion to these ideas. It is due to the interactions within a system that bind its parts that are stronger than the interactions with external systems and internal fluctuations. Cohesion is thus a matter of degree, and has a multidimensional profile depending on the types and probabilities of interactions involved. Cohesion leads to emergence of new properties. This is nicely illustrated with a kite. Lift is a property that depends on the cohesion of the kite. If the kite rips, it looses its lift (Figure 2).
Figure 2. A simple example of how cohesion create global properties

It is common to think of cohesion as a simple linear sum of intermolecular bonds, but in fact the cohesion is much more complicate, with non-linear interactions among the components. This is far more significant in organic systems. It is therefore natural to call the global properties like lift (and biological functionality, including autonomy to be emergent properties of the system.

Within organisation, we can distinguish functionality via its downstream modulation of information and energy flows in the system, and also between the system and its environment\textsuperscript{1,13} I am not clear yet how to quantify functionality (but see Sharov\textsuperscript{15}) for some interesting ideas. This notion can be understood dynamically using the ideas introduced earlier in this paper, with the causal process understood in terms of information flow, especially process closure and interaction closure. This is a rough sketch of how the concrete cases portrayed earlier in the language of function can be understood as concrete cases of dynamical systems without loss of their functional character. It then remains to cash out the promise that autonomous entities thrive best away from harsh selection, and where variety in both the entities and their environments is encouraged. I will speculate that the same principles apply to social and economic systems, and that the widespread but seldom fully explicit Spencerian assumption of Social Darwinism is more harmful than helpful. how the concrete cases portrayed earlier in the language of function can be understood as concrete cases of dynamical systems without loss of their functional character. It then remains to cash out the promise that autonomous entities thrive best away from harsh selection, and where variety in both the entities and their environments is encouraged. I will speculate that the same principles apply to social and economic systems, and that the widespread but seldom fully explicit Spencerian assumption of Social Darwinism is more harmful than helpful.

6. AUTONOMY AND SELF-ORGANISATION

Autonomous systems, unlike the autopoietic systems of Maturana and Varela, which are informationally closed, are open to environmental interaction, especially with environmental information\textsuperscript{4,6}. A system is autonomous if its internal information involved in its controlling its viability is greater than the informational complexity of environmental and internal factors that tend to disrupt the system. Note that a steam engine is not autonomous on this definition. It does not seek out fuel, nor does it alter its activity in order to survive. Computers (at least at present) also fail this test. Viruses, if autonomous, are minimally so. Larger parasites are typically much more autonomous, despite their reliance on features of their host. Humans are somewhat less than maximally autonomous, since they need other humans to be likely to survive, as well as to reproduce. It is questionable whether anything is autonomous in fact.
Semantic information arises when something serves as a sign for something else. Signs are functional entities, their function being to serve as a vicariant for something else. In general, the information modulation of downstream flows represents these flows. Semantic information is thus grounded in pragmatic information. More complex semantic notions involve articulation of this basic form of representation. I describe this in more detail elsewhere. My final comments will be on the role of self-organisation in anticipatory systems. I have already gone into this in some detail in my previous CASYS paper, but I would like to expand on this notion and its advantages (discussed in more detail by Collier and Burch). Forced processes are generally inefficient, requiring large power input and considerable waste. A simple example is the simple harmonic oscillator illustrated in Figure 3.

![Simple Harmonic Oscillator Diagram](image)

At the natural oscillation frequency of the oscillator, it requires little power to make it oscillate. Of this frequency, however, power requirements to get the same strength of response rise rapidly. On of the interesting things about self-organizing system is that they minimize their entropy production when they self-organize, and thus become more efficient. This suggests that forced control is not most efficient.

Many biological systems show signs of self-organisation. In fact their viability requires rather shallow energy wells, and considerable efficiency, suggesting low power organisation. Much more study of both organisation and especially self-organisation in biology is required. This also applies to social systems. Authoritarian and totalitarian states put a premium on control. To some extent, they must rely on predispositions in their populations, but largely they rule by terrorist methods and fear. This requires a large concentration of both political, economic and political power, since driving a system artificially a requires a lot of power and waste of energy. This suggests that such states will be unstable. Unfortunately, whenever there are large concentrations of political, economic or physical power, there will be a tendency to use forced entrainment of ideology, however inefficient. A more efficient but less reliable method is propaganda and advertising, which attempt to drive or create resonances through subtle forcing. This method still requires a concentration of power to exclude competitors.

We believe that a stable social system is best founded on spontaneous entrainment. This is both more stable and more efficient than forced coordination and obedience. Its main problem is that it may lead to arbitrary and unproductive entrainments, basically pathological, so some control is mandatory except in the most advanced social systems, in which stability is already well entrained, and mechanisms for the dissipation of concentrations of power already entrenched in the structure of the system. Great variety can be tolerated in such a system, with minimal control, and it allows both the greatest freedom and flexibility.
7. CONCLUSIONS

I have proposed here a dynamical realist account of functionality that is entirely compatible with the energy based view proposed by George Farre\(^\text{12}\). One advantage of my approach is that it does not require detailed knowledge of energy interactions, or of what is going on at the lowest level, so long as only dynamical processes and states are used in the analysis. Presumably these accounts can eventually be cashed out in Farre’s terms. Only time will tell. In the meantime, the approach I suggest allows rigorous examination of processes at a variety of levels, and is especially useful where information states and flows are the primary considerations. This is likely to be true in most anticipatory systems.

REFERENCES


