SYMMETRY, LEVELS AND ENTRAINMENT

John Collier
Department of Philosophy, University of Newcastle,
Callaghan, NSW 2308, Australia. Email: pljdc@alinga.newcastle.edu.au
http://www.newcastle.edu.au/department/pl/Staff/JohnCollier/

Mark Burch
P.O. Box 1328, Pearl City, HI 96782, USA  E-mail: rhythm@hgea.org

We find symmetry attractive. It is often an indicator of the deep structure of things, whether they be natural phenomena, or artificial. For example, the most fundamental conservation laws of physics are all based in symmetry. Similarly, the symmetries found in religious art throughout the world are intended to draw attention to deep spiritual truths. Not only do we find symmetry pleasing, but its discovery is often also surprising and illuminating as well. For these reasons, we are inclined to think that symmetries are informative. On the other hand, symmetries represent a kind of invariance under transformation, i.e., redundancies. Redundancy, in turn, implies that the information content of a symmetrical structure or configuration is less than that of a similar nonsymmetrical structure. Symmetry, then, entails a reduction in information content. These considerations present us with somewhat of a paradox. On the one hand, many symmetries that we find in the world are surprising, and surprise indicates informativeness. On the other hand, the surprise value of information arises because it presents us with the unexpected or improbable, but symmetries, far from creating the unexpected, ensure that the known can be extended through invariant transformations. How can this paradox be resolved? Rhythmic entrainment is the formation of regular, predictable patterns in time and/or space through interactions within or between systems (resulting in symmetry). The result of entrainment is a simplification of the entrained system. It is the complement to symmetry breaking. Entrainment can be either forced or spontaneous, with the spontaneous form being uncontrollable. It results from processes that are called self-organising. Interestingly, spontaneous entrainment require much less power to form and maintain. It is also the source of levels in systems. I finish with some observations for social systems.

Keywords: symmetry, self-organisation, information, hierarchy, logical depth

INTRODUCTION

The two major themes of this paper, symmetry breaking and the formation of order through rhythmic entrainment, are counterpoint to each other. Together, they are major impetus behind the formation of complex structures in our world, as well as the individuation of those structures. Symmetry breaking separates things, leading to differences and individuation, whereas entrainment creates order and harmony, bringing
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things together into interacting wholes. Together, the two are behind much organisation, from galaxies through living things to recurring chemical processes. The formation of more complex individuated entities implies the formation of new levels of organisation, and many of the new entities formed are emergent from their components (Collier and Muller 1998).

It is convenient to specify these processes in terms of information theory, in order to get some precision, but also to allow comparisons of processes across levels. Physical and some chemical processes can be specified mathematically, but many higher level processes in biology and social systems are most easily specified in terms of changes of form. Information theory is well adapted to quantifying form, and can be applied even at the most basic physical levels (Collier 1999a, Collier and Hooker 1999). Processes themselves are dynamical in the sense that they involve forces and flows, and thus, work and power. It is my belief that everything that is not fictional is dynamical, or can be understood in terms of dynamics. I call this dynamical realism. Dynamical realism is assumed throughout this paper. In using information theory, I do not intend to imply that the world is made of information, but that many things in the world have a form measurable in terms of information. The use of information is convenient as well because it allows ideas of formal and efficient causation to be combined. Since I have dealt with the ideas described in this paragraph in some detail elsewhere (Collier 1986, 1990a, 1990b, 1996a, 1996b, 1999a, 1999b, 1999c, 2000a, 2000b, 2000c, Collier and Hooker 1999, Collier and Burch 2000) I will not go over them in great detail, but will make extensive use of the results.

We find symmetry attractive. It interests us. Symmetry is often an indicator of the deep structure of things, whether they be natural phenomena, or the creations of artists. For example, the most fundamental conservation laws of physics are all based in symmetry. Similarly, the symmetries found in religious art throughout the world are intended to draw attention to deep spiritual truths. Not only do we find symmetry pleasing, but its discovery is often also surprising and illuminating as well. For these reasons, we are inclined to think that symmetries are informative, and that symmetries contain information. On the other hand, symmetries represent a kind of invariance under transformation. Such invariance implies that symmetrical things contain redundancies. Redundancy, in turn, implies that the information content of a symmetrical structure or configuration is less than that of a similar nonsymmetrical structure. Symmetry, then, entails a reduction in information content. These considerations present us with somewhat of a paradox: On the one hand, many symmetries that we find in the world are surprising, and surprise indicates informativeness. On the other hand, the surprise value of information arises because it presents us with the unexpected or improbable, but symmetries, far from creating the unexpected, ensure that the known can be extended through invariant transformations. The first part of this paper will deal with the resolution of this paradox.

Counterpoint to symmetry breaking is the formation of symmetry. Unless it is accidental, this occurs through entrainment. Entrainment is the formation of regular, predictable
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patterns in time and/or space through interactions within or between systems that manifest potential symmetries. We contend that this process is a major source of symmetries in specific systems, whether passive physical systems or active adaptive and/or voluntary/intentional systems, except that active systems have more control over accepting or avoiding rhythmic entrainment. The result of rhythmic entrainment is a simplification of the entrained system, in the sense that the information required to describe it is reduced. Entrainment can be communicated, passing information from one system to another. The paradigm is a group of jazz percussionists agreeing on a complex musical progression.

Spontaneous entrainment creates new symmetries via the dissipation of energy and/or information. Systems tend towards minimal energy and tend to organize themselves so as to minimize dissipation (and consequently loss of available energy within the system – self-organization tends to increase efficiency). This process increases higher level order, or symmetry, and is mutual among the parts of the system, with excess energy being dissipated externally, unlike many cases of forced resonance. Simple examples can be found in resonances in the solar system resulting from tidal dissipation. Resonance tends to reduce dissipation and lower the energy of the solar system, as in all other cases of self-organization. Similar processes are widespread, and more complex cases can direct energy more efficiently than similar forced systems, allowing more effect for less effort. The second part of the paper will deal with this source of new levels of organisation and order.

THE INFORMATION CONTENT OF BELIEFS

In part, the resolution of the paradox involves disentangling the information content of beliefs about a symmetry from the information in symmetrical objects themselves. Although the information content of a symmetrical configuration is relatively low, knowledge that some system is symmetrical reduces what we need to know about the system by eliminating possibilities that would be permitted if the system were not symmetrical. This reduction of required information is greater the more pervasive the symmetry. The relatively low information content resulting from symmetries is reflected in the high epistemic value of knowledge of these symmetries.

The information content of a belief that there is a symmetry in some structure or configuration is a function of the reduction in the number of possible configurations resulting from the elimination of all the ones that are not symmetrical. The more the supposed symmetries reduce the number of possibilities, the greater the information content of the belief in the symmetries. A convenient way to represent the situation was developed by Carnap and Bar-Hillel (Bar-Hillel 1964). They used the resources of inductive logic to define the information content of a statement in a given language in terms of the possible states it rules out from a complete ensemble of states, or state space. For “technical reasons”, largely derived from logical empiricist views of language, they calculated the states ruled out as a number of state descriptions. A state description is a
conjunction of atomic statements assigning each primitive monadic predicate or its negation (but never both) to each individual constant of the language. The information content of a statement is thus relative to a language. This presents no problem as long as the language is powerful enough to represent all possible states in the state space. Evidence, in the form of observation statements, contains information in virtue of the class of state descriptions the evidence rules out\(^1\). Information content, then, is inversely related to probability, as intuition would suggest.

It turns out, though, that our pre-systematic intuitions confuse two different measures of information content, both of which have plausible but incompatible properties. The first measure of the information content of statement \(s\) is called the content measure, \(\text{cont}(s)\).

It is defined as the complement of the \textit{a priori} probability that \(s\) is true:

\[
\text{cont}(s) = 1 - \text{prob}(s)
\]

The \textit{cont} measure correctly represents the complementary character of information and likely configurations, but it has a serious problem.

\textit{Cont} fails the additivity condition, according to which the combined information content of two inductively independent statements\(^2\) should be the sum of their individual information contents (Bar-Hillel 1964: 302). This condition is required in the present context, since we are interested in the information difference between a state description without symmetry and the state description with symmetry. The \textit{cont} measure also fails some natural assumptions about conditional information. These problems motivated the introduction of another measure, called the information measure, \(\text{inf}(s)\):

\[
\text{inf}(s) = \log_2 \frac{1}{\text{cont}(s)} = -\log_2 \text{prob}(s)
\]

The value of this measure is in bits. Although \(\text{inf}\) satisfies additivity and conditionalization requirements, it has a property that some people find counter-intuitive. If some evidence \(e\) is negatively relevant to a statement \(s\), then the information measure of \(s\) conditional on \(e\) will be greater than the absolute information measure of \(s\). This violates a common intuition that the information of \(s\) given \(e\) must be less than or equal to the absolute information of \(s\). The content measure, \(\text{cont}(s)\), does satisfy this intuition (Bar-Hillel 1964: 306-7). Personally, I do not share this widespread intuition, since it requires effort to correct the inference based on \(e\) that \(s\) is less likely.

On the \textit{inf} measure (and the \textit{cont} measure as well), if there is no knowledge of the state of the system, all state descriptions are equally likely, and \(\text{inf}(s)\) takes on its lowest possible

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\(^1\)Carnap and Bar-Hillel, as was the custom at the time, assumed that observation statements can be connected to experience unambiguously. This assumption turns out to be problematic; I discuss the problems in (Collier 1990). While no resolution is widely accepted today, the problem does not seriously effect the general principle proposed by Carnap and Bar-Hillel.

\(^2\)Inductive independence means that the conditional probability of each statement given the other is the same as its initial probability.
value. Any evidence which disturbs this equiprobability, including evidence of symmetries, increases the information we have of about the system. The information involved will be the difference between the Shannon entropy of the ensemble of equiprobable states and that of the ensemble of states permitted by the evidence. The Shannon entropy, $H$ is the weight sum of the inf:

$$H = - \sum_{i} \text{prob}(s_i) \inf(s_i)$$

[3]

This is maximal if all of the inf(s)s are equal, i.e., all the s’s have the same probability. The difference is then:

$$H_{\text{sym}} = H_{\text{max}} - H_{\text{act}}$$

[4]

The latter entropy represents the information content of the symmetries in the system, assuming that the only evidence we have is about symmetries. In other words, knowledge of symmetries within a system produces information about the possible configurations ruled out by the symmetries. This information will be greater the less the information in the symmetries, this information being less the more pervasive the symmetries in question. Symmetries, then reduce the knowledge we need to understand the system. This would make them interesting epistemologically.

It would be hasty, however, to think that this completely resolves the paradox. Any new knowledge has much the same effect as knowledge of symmetry. Consider an experiment (a roll of a die, for example), with possible outcomes $O_1, \ldots, O_n$, in which we discover $O_i$ is the case. $O_i$ reduces the possibilities in much the same way that learning of a symmetry does. Symmetries are interesting over and above their interest as the outcomes of experiments. Also, while the outcome of an arbitrary experiment might be quite specific, and hence have a relatively high information content, symmetries are always of relatively low intrinsic information content. We still need to explain the interest of symmetries, despite their relatively low information content. I will offer an answer that distinguishes between surface and deep symmetries, and argues that deep symmetries are interesting because of the way that information originates in symmetry breaking. I will first look at the mathematics of information and symmetry, and then at some specific ways in which information originates in thermodynamic, cosmological, biological and perceptual processes.

**INFORMATION AND REDUNDANCY**

The basic idea of information is that of a distinction between two things. In standard language the notion is restricted to recognized distinctions, or at least ones that are in a position to be recognized, but information theory, as it has developed in abstract mathematical form, does not restrict itself to just meaningful distinctions, but to any distinction. This idea has three roots: i) logic, which can be traced back to Leibniz at least, but reaches its fullest form in the algorithmic complexity theory, which gives a measure of information in terms of the minimal number of distinctions needed to identify
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something uniquely, ii) physics, going back to Maxwell and his demon, but expressed more clearly by Szillard (1921), Schrödinger (1946) and Brillouin (1962, and finally iii) communications theory, due to Shannon (1949). We will have little to say about the last because of its highly specialized nature. Ideally, the three approaches should be unified, but such a unification is still in the future. One thing that can be said, is that any unification must be able to explain how information can be dynamically, or causally based, with the logical and communications theory forms being abstractions.

There are three (almost) equivalent approaches to mathematical information theory: combinatorial, probabilistic and computational (Kolmogorov 1965). On all three approaches, redundancy is a reduction in information. The combinatorial and probabilistic approaches are essentially statistical, and apply most aptly to ensembles of similar systems, although they can be adapted to deal with individual systems with statistical properties (Penrose 1970; Collier 1990a, 1990b). The computational approach is more general, since it can apply to any system showing order of some sort, but it is most usefully applied to individual, non-statistical systems (Collier 1990a).

On the combinatorial approach, information depends on frequencies of microstates making up a macrostate within an ensemble, or the frequencies of identical components within an overall configuration, much as described by equation [3], except with prob(s) replaced with freq(s). The probabilistic account is similar, except that probabilities rather than frequencies are used, giving equation [3] exactly. As in the combinatorial account, the probabilities can refer to probabilities in an ensemble of configurations, or to those of elements in a single configuration, though in this case the former interpretation is more natural. These definitions of information can be taken to be entirely abstract, without regard to their physical embodiment, but when they refer to physical systems, the possible states are called complexions. In what follows, I will assume that information is taken to be physically embodied, as required by dynamical realism. Assuming this, a point to note is that the average information per complexion in [3] is the negative value of the entropy of the system. This relation is known as the negentropy principle of information (Schrödinger 1944, Penrose 1970). The information in a physical system is then given by $H$ in equation [4].

The computational, or algorithmic approach (Kolmogorov 1965, 1968; Chaitin 1975, Li and Vitányi 1990) is motivated quite differently. The fundamental hypothesis of algorithmic information theory is that the information content of something is the length of the shortest (self-delimiting) program in binary form that can produce it:

$$I_{\text{Alg}}(s) = \text{length}(s) - O$$

[5]

Where $O$ is an additive constant. The idea behind this hypothesis is that a thing can be specified by making a series of binary distinctions (Spencer Brown 1972). The minimum number of distinctions required is its information content in bits$^3$. The algorithmic

$^3$The logic of distinctions can be shown to be equivalent to Boolean algebra (Banaschewski 1977, Cull and Franck 1984). This reflects the relation between information and the minimal number of distinctions, where
Definition of information content is equivalent to the combinatorial and probabilistic information contents except for an additive constant representing computational overhead (Kolmogorov 1968) that can be made arbitrarily small (Chaitin 1975). The basic concepts of information theory can be defined without recourse to probability theory, and are applicable to individual cases (Kolmogorov 1968). Furthermore, the relations between information and probability allow probability theory to be based on algorithmic information theory.

On each of these accounts, redundancy is either a direct repetition of information, or else a correlation within the structure that constrains the amount of information that it can hold. The simplest sort of redundancy is simple repetition of elements. Another form of redundancy occurs when each element constrains the next possible element (Markov redundancy). Higher order redundancies are also possible, in which correlations occur over sequences of N units that cannot be found in fewer than N units. These show up in the presence of deep symmetries. The basic mathematical theory of information, including levels of redundancy, was developed by Shannon (Shannon and Weaver 1949), but the notion of depth is much more recent. The only suitable formal definition at present is *logical depth* as defined by Charles Bennett (Bennett 1985, Li and Vitányi 1990). It is a measure of the computation time (or number of steps) required to produce the surface structure of a sequence from its most compressed form. Simple repetitive redundancy is relatively easy to compute, but redundancies relying on long sequences of elements, or on mutually constraining elements spread broadly over a sequence, are much harder to compute from their maximally compressed form (but see Collier and Hooker 1999).

**Symmetry Dynamics**

A symmetry is fundamentally an invariance of a configuration of elements under a group of automorphic transformations (Weyl 1952). An automorphic transformation is one that maps the elements of a system onto elements of the system such that each element is mapped onto exactly one element by the transformation. Symmetry can be defined as an automorphism, and the degree of symmetry can be completely characterised by the set of transformations that bring the system or configuration into coincidence with itself. (Aleksandrov et al 1969: Vol. III, pp. 271-2). The identity transformation exists for any system. If the identity transformation is the only automorphism, the system is unsymmetrical. Other automorphisms produce non-trivial transformations, indicating a non-trivial invariance. This invariance implies that the configuration is redundant, because it implies correlations within the system or configuration. The complementary mathematical character of the relation between information and symmetry suggests that information might always originate in symmetry reduction. It might seem possible that each bit of information can be thought of as representing the answer ‘true’ or ‘false’ to a set of well chosen questions, much like a perfect game of “20 questions”. This was noted by Donald MacKay (1969). It means the information string is a line in a truth table that defines the thing.
information might have other sources than symmetry breaking, but there is a close tie between equilibrium and symmetry (Weyl 1952: 25. Under equilibrium conditions, equation [4] has a value of 0, and there is no information.

With these formal definitions of information and symmetry, we can examine where information originates in the universe. If all nature were entirely lawful, then nature would be fully symmetrical, reflecting the dynamical symmetry of the laws (Weyl 1952). In order to account for non-symmetries, we need contingency, which arises either from initial conditions, or else from symmetry breaking processes. On the “no boundary conditions” cosmology favoured by many modern cosmologists, there is no information in the initial conditions (they are entirely symmetrical) (Layzer 1990), so all information must arise through symmetry breaking. Any cosmology that does not make this assumption is incomplete, since any deviation from statistical equivalence is in need of further explanation. Since the no boundary conditions condition implies that all complexions are statistically equivalent in the original state of the universe, the initial cosmological condition is one of macroscopic equilibrium. Unless this is so, we are faced with an infinite regress of cosmological explanations. Subsequent symmetry breaking that produces information occurs in processes in which microscopic fluctuations are promoted to macroscopically detectable structure.

There are two types of symmetry breaking that occur in the early universe. The first is the differentiation of matter and radiation. This occurs when the rate of equilibration between matter and energy (the relaxation rate) falls behind the expansion rate of the universe. This leads to the formation of branch systems that require more information to describe than either the original statistically uniform condition or the local equilibrium condition that immediately precedes the phase separation of matter and radiation. Layzer notes that there is not only structural order in the universe, but also chemical order. The origin of chemical order is a major focus of Steven Weinberg's book, *The First Three Minutes* (Weinberg 1977), which deals primarily with the formation of matter. As Weinberg points out, the first 1/100 sec is hidden to us because the high energies involved are of the same order as those of nucleons (hadrons in general) (over 100,000 million degrees Kelvin). But the strong force, governing nucleon interactions, has a constant analogous to the fine structure constant of the weak force whose value is close to unity (compared with 1/137 for the fine structure constant), so nucleons interact very strongly. So strongly, in fact, that it is not clear it is possible to separate their components, even if there are some elementary components (varieties of quarks). There is no clear sense in which there is a definite number of particles under these conditions.

At lower temperatures, we get separate particles, but they are in thermal equilibrium until roughly 10,000 million degrees Kelvin (1.09 seconds duration), when neutrinos are no longer in thermal equilibrium. As temperature and density decrease, they work synergistically to lower the rate that fluctuations return to equilibrium. The rate of interactions among particles that causes relaxation to equilibrium depends on the mass density directly, whereas the rate of expansion depends on the square root of mass density, so there is a point at which the rate of expansion exceeds the relaxation rate, and
we start to get branch systems forming as the universe goes out of thermal equilibrium. Interestingly, after this time the maximum possible entropy rises faster than the actual entropy, and order and disorder increase together. This permits information to increase at the same time as entropy. Before that time, there is no spatial entropy gradient, and even though global entropy increases, the local conditions are near to equilibrium, since the size of fluctuations is greater than the entropy gradient, and the relaxation time is short enough that fluctuations decay before they can stabilise. The universe was effectively completely symmetrical at the macroscopic scale because it was at equilibrium, and the microstates were statistically equivalent, since they were initially statistically equivalent, and no source for the information required to distinguish them existed.

Similar processes continue to produce information as the universe develops. The classic example is Bénard cell convection in a fluid gently heated from below. If other parameters making up the Rayleigh number are kept constant, the onset of convection depends on the temperature gradient through the fluid. The system is too difficult to analyze at the microscopic level, so standard treatments compare the dynamics of conduction with those of convection, and determine the transition Rayleigh number from the convergence of the equations at the onset of instability. The condition of conduction is symmetrical at all levels (except for statistical fluctuations), but the onset of convection introduces new symmetries at the macroscopic level, while at the same time destroying some of the microscopic symmetry (some microscopic automorphisms are ruled out by the macroscopic movement of molecules in the fluid).

Sympatric (same locale) speciation can occur via similar processes, as can tissue differentiation during biological development (Collier et al, in press). In both cases differentiation, a form of symmetry breaking, is not under the full control of either exogenous or endogenous information. Chance fluctuations play a central role in the exact pattern of information formation. There is increasing evidence that much biological information is produced by such symmetry breaking processes (Brooks and Wiley 1988; Kauffman 1993; Collier and Siegel-Causey, in press). One of the major mechanisms that has been proposed to drive this sort of process is self-organisation permitted by non-equilibrium processes, where non-equilibrium conditions are maintained by a continually expanding state space within a branch system (Brooks and Wiley 1988). There is a very strong analogy to the formation of information through symmetry breaking in cosmological processes.

It has been proposed that at least some perceptual systems (smell and hearing) involve chaos in the transducer and associated neurons (a condition of symmetry) that is driven by a sensory signal into a particular harmonic orbit of the many quasi-harmonic orbits that compose the chaotic condition (Skarda and Freeman 1987). If all perception works similarly, then perception is a form of symmetry breaking that produces perceptual information. The information, in this case, comes from outside the perceptual system.

\[\text{4The equations and a physically motivated discussion of Bénard convection and its implications for self-organisation appear in (Collier et al in press). The classic analysis is by Chandrasekar (1961).}\]
However, from inside the system the original condition is statistically symmetrical, and the asymmetry is produced by the internal dynamics of the system under the influence of a relatively small driving force. The response of the system, if these controversial proposals are correct, is much stronger than the stimulus producing it. Perhaps the same principles can be extended to cognition, as well as perception. At present this is pure speculation, but it is certainly possible that concept formation and theory formulation in the face of incomplete evidence is also partially driven by self-organising processes that provide information beyond that contained in the evidence available. If so, symmetry breaking is fundamental to many cognitive processes as well as to perception.

To recapitulate, the original condition of the universe is statistically uniform, and hence entirely symmetrical. This statistical uniformity implies an equilibrium state (at least locally), which further implies that the early universe did not contain any information. Information, therefore, must have arisen through contingencies. The only process we know of that can produce new information from contingencies is symmetry breaking through phase separation in a system that is out of equilibrium, thereby forming branch systems. Similar branching is repeated at smaller scales as the universe differentiates and forms new branch systems (Layzer 1990). This process can either be driven by forces externally applied to a system far from equilibrium that drive the system to self-organise to a more stable state, or can arise endogenously through self-organisation resulting from non-equilibrium conditions maintained through an expanding state space within a branch system. In both cases, the appearance of new information depends on symmetry breaking permitted by the promotion of microscopic fluctuations on a statistically uniform background under conditions that are not at equilibrium. Non-equilibrium conditions permit symmetry to be broken, by allowing the sort of contingency that Weyl requires to overcome the universal symmetry implied by natural laws alone.

WHY SYMMETRY IS INTERESTING

Given that information production is symmetry reduction, the problem of the interest of symmetries becomes acute. Not all symmetries are equally interesting. Many symmetries are purely superficial, being either convenient or accidental, traceable to equilibrium conditions (which wipe out information), or both. These symmetries have little logical depth, and are relatively easy to produce. Examples are symmetries found in crystal structures in typical minerals (not the so-called “aperiodic crystals” that are found in complex biological molecules), many utilitarian human artefacts, and the obvious symmetries, radial and bilateral, found in animals and some plants. The main interest of these symmetries is in the information reduction produced by our knowledge of them, together with possible advantages of having the redundant systems that these superficial symmetries imply. This is not incompatible with our having an aesthetic appreciation, or

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5Radial and bilateral symmetry are not themselves adaptations, but are left over from the spherically symmetrical structure of primitive organisms (phylogenetically), and of the fertilised ovum (ontogenetically). Adaptations produce deviations from this ur-symmetry.
even fascination, for superficial symmetries, but it does mean that this appreciation will never penetrate deeply.

Deeper symmetries, however, are left after symmetry breaking process produce information at higher levels. These symmetries are much more interesting. Their interest, I propose, is in what they reveal about the common source of different informative structures that arise from them. The deep symmetries highlight the individuality of derivative structures, and also make their common nature more clear. Their recognition allows us (and forces us) to see the sorts of symmetry breaking – information – that make up the different structures emanating from a common source. The symmetries behind natural laws don’t merely provide a convenient shorthand to compress our empirical data; they also help to highlight both the particular and the general in that data in an especially insightful way.

To take one example, the Law of Conservation of Energy (the First Law of Thermodynamics), like all conservation laws, is a symmetry law. As a universal physical law, it requires that the possible physical transformations are restricted to the ones that maintain the symmetry implied by the law. Newton’s laws themselves do not imply conservation of energy (dissipative forces are not ruled out), though each of Newton’s laws implies other symmetries (consider, for example, the law of reaction). Additional assumptions invoking symmetries at least as strong as conservation of energy must be made in order to derive the energy conservation law from Newtonian mechanics. One of the simplest such assumptions is that all forces are conservative. This principle imposes a condition on systems that the sign of the time parameter in a dynamical description of a system can be substituted with its opposite, and the resulting system is equally possible physically. The condition also requires that any temporal translation of a system will make no difference to its dynamics. These requirements greatly simplify the set of possible physical systems, and they worked well with atomic and molecular systems, as well as loosely coupled systems like the solar system. The recognition that heat is a form of motion of microscopic particles under the influence of conservative forces allowed the extension of the principle to dissipative systems. The principle underlies the applicability of the elegant Hamiltonian formulation of mechanics, which has been extended to fields, waves and quantum systems. The generality of the Hamiltonian formulation also allows the introduction of generalised coordinate systems, which further extends its applicability and ease of use (cf Collier and Hooker 1999).

Conservation of energy is a simple principle, but it is not at all obvious how it is to be applied to all physical systems. In fact it took many years to give an adequate account of thermodynamic systems in mechanical terms, and the account still has some problems. The striking thing is that such a wide variety of systems, which appear quite different on the surface, can be described by the same basic equations, all on the assumption that the total energy, kinetic and potential, of an isolated system is a constant. At the same time as the systems are taken to obey the same basic symmetry, their surface structure can be quite different. The application of the Hamiltonian formulation highlights both the
underlying common characteristics of all physical systems, but the details of the application in each case highlights their differences.

The energy conservation principle is quite deep, since it is often not apparent how to apply the principle to individual cases. Some possible physical systems are so complex that there is no way to apply the principle analytically, and the best we can do is to make approximations. Nonetheless, the unifying power and simplicity of the principle leave little doubt that it should apply to all physical systems, even if this cannot be proven rigorously. In fact, the very difficulties encountered in applying the principle to certain types of systems helps to explain the nature of those systems, and how they differ from systems to which the principle can be more easily applied. I have argued (1999a) that all causation is an invariance (symmetry) of information instances. If dynamical realism is true, and my account of causation is correct, then we can say the same of all causal systems, since causal relations are the deepest that exist. I have argued (Collier 2000a) that a dynamical informational analysis can be applied more easily than energetic analysis to many types of higher level systems.

I would like to speculate that the aesthetic value of symmetries (aside from their artistic use to point to other things) is a reflection of the basis of their scientific interest (a symmetry underlying symmetry!) Shallow symmetries are boring and repetitive; too much symmetry is bland. When surface characteristics are underlain by a recognisable deep symmetry, however, the symmetry ties together the individual parts without denying them their individual interest or identity. At the same time as it gives an overall harmony and unity, deep symmetry highlights the individuality and unique interest of the parts of a composition or natural phenomenon. Appreciation of deep symmetries allows a much richer experience than would be possible otherwise. Although evolutionary biologists have tried to explain our taste for symmetry in terms of the health of potential mates, I suspect that its basis is much more deeply embedded in our nature, and in our relation to the world at large.

**RHYTHMIC ENTRAINMENT**

Rhythmic entrainment is the formation of regular, predictable patterns in time and/or space through interactions within or between systems that manifest potential symmetries. We contend that this process is a major source of symmetries in specific systems, whether passive physical systems or active adaptive and/or voluntary/intentional systems, except that active systems have more control over accepting or avoiding rhythmic entrainment. The result of rhythmic entrainment is a simplification of the entrained system, in the sense that the information required to describe it is reduced. Entrainment can be communicated, passing information from one system to another. Rhythmic entrainment can either be forced (driven) or spontaneous (self-organizing). Forced entrainment can be either high power or low power. In high power entrainment, one powerful system drives another through immediate force, e.g., a boat’s movements on storm waves at sea. Low power forced entrainment is of interest because it depends more on persistence and
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careful application of force than on immediate power. An example would be driving a
large oscillator (say a swing) with small applications of force just off a node (“pumping”
the swing). Forced cases always transfer pre-existing order. Forced resonance can be
destructive, as when a singer shatters a glass by driving it at or near its resonant frequency
too strongly.

Spontaneous entrainment, on the other hand, creates new symmetries via the dissipation
of energy and/or information. Systems tend towards minimal energy and tend to organize
themselves so as to minimize dissipation (and consequently loss of available energy
within the system – self-organization tends to increase efficiency). This process increases
higher level order, or symmetry, and is mutual among the parts of the system, with excess
energy being dissipated externally, unlike many cases of forced resonance. Simple
eamples can be found in resonances in the solar system resulting from tidal dissipation.
Resonance tends to reduce dissipation and lower the energy of the solar system, as in all
other cases of self-organization. We argue that similar processes are widespread, and that
more complex cases can direct energy more efficiently than similar forced systems,
allowing more effect for less effort. Rhythmic entrainment is a counterpoint and
complement to the production of information by symmetry breaking, though similar
principles are involved. In particular, both symmetry breaking and rhythmic entrainment,
when spontaneous, are the result of dissipative forces (of which friction is a paradigm).
The two processes are responsible for much (if not all) of the complexity and organization
in the Universe.

This section focuses on the connection between information and effort. Producing
information requires effort, or work, which in turn requires available energy, sometimes
called exergy. Maxwell recognized that the statistical account of the Second Law of
Thermodynamics, that the entropy of an isolated system does not decrease, in all
probability, would be violated by a sorting demon that could sort fast and slow molecules.
Szillard (1921) showed that such a demon was impossible, because to get the information
to do the sorting, the demon would have to expend at least as much exergy as would be
 gained by the sorting. Schrödinger (1946) suggested that information of the sort found in
biological and other organized systems was negentropic, and this idea was codified by
Brillouin (1962) as the Negentropy Principle of Information (NPI). NPI implies that in
order to do a measurement, work must be done, and exergy dissipated. Not only that, but
any formation of order requires the dissipation of an equivalent or greater amount of
exergy. More general proofs for computational systems were given by Landauer (1961,
1987) and Bennett (1982), who showed that a sorting demon would have to have an
infinite storage place for waste information in order to work; erasure leads to lost
information and consequent entropy increase. Collier (1990b) gave a proof by reductio
that a dynamical demon could not reverse the flow of entropy without some supernatural
or very lucky source of information. The Second Law is empirical, but the connection to
information through the arguments for the impossibility of a sorting demon establishes
that producing information requires work. Conversely, dissipation of energy leads to a
loss of information.
Recent work in logic sheds some light on the relation between information and causation. Given NPI, and the reasonable assumption that all properties supervene on causal properties (that is, there can’t be two worlds with the same causal properties that differ in additional properties, or, alternatively, dynamical realism is true), causation is equivalent to the transfer of the same instance of information (Collier 1999a). The only way new information can appear is through work, but information can dissipate spontaneously. This notion of causation guarantees that work requires that entropy not increase, and that obtaining information requires work. This allows us to define a dynamical system in information theoretic terms.

Consider what individuates a system. If it is not just a nominal system, then it is individuated by causal connections within the system that bind it together. Collier (1988) introduced the notion of cohesion to refer to the closure of the causal connections within a system that unify it and separate it from other systems. Collier and Hooker (1999) have refined the idea to a cohesion profile, which is a multidimensional probabilistic description of the unity dynamical conditions. The basic requirement for dynamic individuality is that the cohesion profile of the system is stronger than any cohesion profile that can be constructed involving other components. Thus cohesion both unifies a system and distinguishes it from other systems, providing the individuation conditions for dynamical systems. The information in the cohesion of a system cannot be completely localized, since any system is spread over space and time. In simple systems, for example a rock crystal, the bonds are local, and the information will be highly redundant. In an ideal gas in a container, all of the information of cohesion of the system is given by the macroscopic thermodynamic variables and the information of the cohesion of the container. Most systems are someplace in between. Highly organized complex systems will show information at a high level of redundancy, that is, it requires large sequences to detect the redundancy. Bennett (1985) has suggested that organization can be measured by the time (number of steps) it takes to compute the surface structure of a string from its compressed form. One of the consequences of this idea is that organization so defined will show high order redundancy. In any case, complex organized systems will not have maximal information (they won’t be random), and they won’t have minimal information (they won’t be highly redundant). We can also expect that they will take time to produce, at least in the initial instance (reproduction from a template can be done more quickly). Also, they require effort to produce the information, which will be relatively high, whether in the initial case or from a template. Quick organization will be inefficient, requiring considerable power, much of which is likely to be dissipated in the process. On the other hand, spontaneous self-organization of complexly organized systems is a slow process, but can be much more efficient from an energetic point of view. The formation of such systems often involves a combination of symmetry breaking to produce complexity and entrainment to produce order. Even in manufacturing processes, raw materials are usually purified and/or cut into pieces and then reassembled. In spontaneous cases, like the formation of Bénard convection cells, symmetry breaking and entrainment can occur together. Generally, however, complexly organized systems will have a long iterative history of such processes, as well as sorting by selection. This is all rather
Symmetry, Levels And Entrainment

The details can be found in the references of (Collier 1999a and Collier and Hooker 1999).

Cohesion requires entrainment, but entrainment does not imply cohesion: two independent systems can be entrained, but the connection may not be strong enough to create cohesion; connections to other systems may be stronger. In many cases, however, entrainment and cohesion go together, as in a jazz combo playing a specific piece of music. One might imagine that rhythms from external sources are picked up and developed in the piece, but they would not thereby become part of the piece of music. When entrainment does become strong enough to produce cohesion, a new level is formed; we can talk of the emergence of new properties. Without cohesion, we have interacting parts, but no new level.

A taxonomy of rhythmic entrainment starts with the split between forced and spontaneous entrainment mentioned in the introduction. Forced entrainment, sometimes called driven, can be either high or low power. For example, the movement of a boat on a strong sea is driven by high power, and the boat is at the mercy of the sea. A typical low power system is one in which the driving force is applied in small amounts near to nodes of oscillation of the system, as when a child “pumps” a swing to make it move in larger, more energetic arcs. Many processes, like driving a car, combine both high and low power entrainment: the motive force is high power, but it is directed by relatively low power movements of a steering wheel. Control systems in general are low power, but can control large energy flows. To some extent, control is most easily thought of as an informational process, but the distinction is rather arbitrary. Forced entrainment always transfers preexisting information, either through reorganization or through a template. It does not create new information types, but at most new instances of preexisting types. Forced entrainment is especially important for discussion of measurement and perception, but it is also useful as a contrast with spontaneous entrainment. There is no reason, though, why both forced and spontaneous entrainment cannot occur in the same process, as probably happens in the development of organisms and other biological systems (for three quite different accounts, compare Kauffman 1993, with Brooks and Wiley 1988, Brooks et al 1989, and Collier et al in review, and with Weber et al 1989 and Schneider and Kay 1994).

Spontaneous entrainment always involves dissipation of energy. A simple example, is when a bunch of lipids spontaneously form a sphere because one end is polarized; the energy lost in forming this configuration is most likely expelled as heat, but whatever, the entropy of the system and its surroundings will increase. The same thing happens when ice melts, with the difference between the frozen water and its liquid state known as the latent heat of fusion. There are much more complex cases in nature, however, which in many cases have involved both spontaneous self-organization and selection, as in organisms, species and ecologies (for a broader account, see Collier and Siegel-Causey, in review). Notice that when the lipids form a sphere, symmetry is formed, and a new level, that of the lipid sphere is formed. This case can be analyzed almost entirely mechanically, but many case that are not much more complex cannot, such as the onset of convection in Bénard cells. The analysis of this transition assumes the convection, and equates the
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equations of motion for the convecting and conducting cases to determine the conditions at convection onset. A derivation of the convecting state from first principles of molecular motion is almost certainly impossible because the motion is chaotic. We can predict convection because we have observed it before, and the Bénard cell case is carefully controlled to have only one end state or attractor. In unobserved cases prediction is more difficult, and in cases with many attractors prediction is impossible in principle, and this makes it uncontrollable except in general characteristics. This uncontrollability is characteristic of complex self-organizing systems such as ecologies, societies, and economic systems. A major practical problem is what we can do about these circumstances. It is time for some more specific examples.

PHYSICAL EXAMPLES

Mechanical systems

Some of the most interesting spontaneous symmetries are in the Solar System. One obvious one is the 1:1 correspondence between the Moon’s rotation and revolution times. This is typically attributed to tidal torques lagging behind the direct line between the Moon and the Earth that create dissipation of gravitational energy. The torques are minimized if there is a 1:1 correspondence, since then there is no lag. There are some other much more complex resonances, however. Mercury’s rotation period is in a 3:2 relation to its revolution period around the Sun; i.e., Mercury turns three times on its axis for each time it goes around the Sun. This can also be accounted for in terms of tidal torques, since they are less in a 3:2 resonance than in any nearby relation (though greater than they would be for a 1:1 relation, in which there would be no tidal torque). Therefore, Mercury is effectively caught in the 3:2 resonance. How did it arrive in this resonance, rather than some other? Basically, the answer is chance. In the total Sun-Mercury phase space with tidal dissipation there are a number of attractors representing resonances, with fractal boundaries between the resonance basins. With no other information, there is about a 30% chance of 3:2 resonance, 50% for 1:1, and the other cases cover the other probabilities. Further resonances are a near 5:2 between the rotation period of Venus relative to its passing the Earth, and a resonance between Pluto and Neptune such that although Pluto crosses the orbit of Neptune, it will never hit Neptune (this may be partially a relic of Pluto having been a moon of Neptune at one time).
Physics also provides good examples of forced resonances, as when a force drives an oscillator towards its natural oscillatory frequency (nearby frequencies are damped by dissipation, so not any frequency can be driven unless there is considerable power and lots of energy to waste). Even chaotic oscillators can be put into resonance; the resonance itself is harmonic, but the motion of each oscillator is chaotic. This shows the possibility of forcing a resonance in an otherwise unpredictable system. The expense is dissipated power.

There are many other cases of spontaneous entrainment in physics. One especially simple case is the formation of dissipative structures through the promotion of noise. Bénard convection cells are the simplest of these, since they are so closely controlled. Nonetheless, the cells form spontaneously when the conditions are right. Other forms of entrainment are seen in the formation of eddies, standing waves in streams and waves in the atmosphere. In each case the entrainment creates a macroscopic structure that contains symmetries not present in the original microscopic structure. Although it is possible to create circumstances that will produce a certain resonance, in systems with multiple attractors this can be done only probabilistically, undermining controllability (large applications of power and dissipation of energy are required to overcome this lack of uncontrollability). In systems like the climate and weather, with many attractors, control is virtually impossible, since very small effects can move the system from one attractor to another (the so called “butterfly effect”).

Several lessons can be learned from the physical cases. First, for the forced case, there are natural resonances in certain systems that can be driven by forces that contain the relevant
frequency. The oscillator will resonate at its natural frequency because other frequencies will be damped by dissipative forces. To drive a system at an unnatural resonance requires a great deal of power, and wastes a lot of energy to overcome dissipation. We believe that the same principles apply across all systems for forced resonance, including social systems. In the case of spontaneous resonance, the properties of the system imply attractors to which the system can be led by dissipation. Systems with multiple attractors are hard to control, and like forced oscillation, require considerable power to drive them to a desired attractor, or else very subtle applications of force in regions near the chaotic zone between attractors. There is an interesting case of a Japanese satellite that was supposed to go to the moon, but lacked the power due to other problems. NASA, who launched the satellite, worked out that there was a chaotic region in the earth-moon-sun system, and by applying a small amount of force near that chaotic region, transferred the satellite into a lunar orbit from a terrestrial one. Of course the journey took longer than just blasting the satellite to the moon, but it achieved the purpose.

**Chemical Systems**

Lipid spheres were mentioned above. Many other self-organizing chemical processes are similar, but depend on various thermodynamic parameters. Some specific chemicals have interesting properties from the perspective of symmetry and cohesion. Benzene, for example, is a closed loop of six carbon atoms with double bonds that oscillate. This spreads the cohesion of the molecule over the whole bond structure, and increases cohesion and hence stability.

Another case involves the comparison between ethylene and butadiene (Harris and Bertolucci 1988: 288-297). Ethylene is a double-bonded 2 carbon unit. Butadiene is a 4 carbon unit with 2 double bonds. To make all things equal, the energy of 2 molecules of ethylene is compared with one molecule of butadiene. The butadiene is more stable by 12 kJ. The usual explanation is that the bond energy is delocalized, but it is not clear why delocalizing something should lower its energy. Our explanation, that there is increased cohesion in the form of harmonic entrainment of the bonds explains why the energy of butadiene is lower.

Presumably more complex chemical systems as found in organisms increase stability through similar nonlocality (although not through double bounds, but networks of pathways, even though the individual molecules are not necessarily especially stable). The thing to note is that it is the whole network that inherits the stability. We could go on about similar issues in development, evolution and ecology, but these have been studied extensively elsewhere (ecological studies by Robert May introduced much of the interest in the general topic).

**SOCIAL SCIENCES**

The communication of memes is one of the most interesting forms of entrainment. Memes can be ideas, practices, ideologies and paradigms, among other things, though
they are most often thought of as ideas. In some cases, when the basic primitives are already there, memes are passed by simple resonance, causing an appropriate combination of preexisting memes. In other cases, new primitives must be created, as when an apprentice learns from a master. This involves some simple forcing through recombination, but largely involves the spontaneous generation of memes through the generation of new primitives in the apprentice in the presence of the master’s memes, which aid in the entrainment through reward and punishment, but also through copying and practice directed in an appropriate way. This latter form of learning can be carried out independently, and is probably a major factor in the transmission of memes. The basic primitives are already available to the apprentice, and he can reorganize them for new tasks, but mastery comes only when the memes are integrated into the autonomy of the apprentice, so the apprentice can discover new ways to work, and achieve mastery. The passage from childhood to adulthood is not dissimilar. The new organization requires both differentiation and entrainment, and requires much experience and practice.

The original metaphor for entrainment from music is a social case, and we believe that entrainment is common at the social level. This can help to create social order and function, but it can also be wasteful and counterproductive if done poorly. In some cases practices, ideas and ideologies form spontaneously and unpredictably when the right conditions occur, resulting in very rapid change. Changes in fashion and art and the fall of the Berlin Wall probably contain large elements of this sort of entrainment. The population affected need not be prepared for the eventuality, but there must exist a social attractor (perhaps one of many), that random variations allow to become expressed throughout the population. If there are many attractors, the change will be essentially unpredictable, and in that sense random. This suggests that there will never be a fully predictive social science, especially in the case of history.

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.

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.
CONCLUSIONS

Dissipative processes can produce both information and order, both of which are required for the development of complexity and organisation. The mechanical model persisting since Newton’s time suggests the forced model of entrainment. This alternative self-organizing model can explain many phenomena, and even has social and economic repercussions. It explains why authoritarian systems need to use a lot of power (making them inherently unstable), and why a self-organizing system, perhaps with gentle control, needs less power and is more stable and self-sustaining. The lessons are from physics and biology, but the extend to systems in general, whether management, social or economic. These higher level systems show an organization that makes them cohere, and follow their own rules ensuring their emergence (Collier and Muller 1998). On the other hand, a system with enough flexibility and variety can also go through bifurcations and phase changes that can be largely unpredictable. Perhaps this is necessary for creativity, but useful results are not guaranteed; therefore some filtering mechanism is required. Perhaps the best management strategy is to encourage variability and novelty with a moderate degree of selection. Contrary to the competitive model of “nature red in tooth and claw”, the most stable and self-sustaining systems require the encouragement of variety and gentle control. A strict selective regime will stifle creativity and forced control requires large amounts of power. It may seem that harsh conditions and discipline produce the best results, because the results can be well-defined and worked towards. I believe that this leads to resistance within the system, and a tendency to miss optimal solutions. A more gentle environment encouraging variety is more likely to come across better solutions, and is less likely to get caught on local maxima.

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