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Order From Rhythmic Entrainment and the Origin of Levels Through Dissipation

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Abstract: *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. The paradigm is a group of jazz percussionists agreeing on a complex musical progression. The process of rhythmic entrainment is complementary to that of symmetry breaking, which produces information. The two processes account for much, if not all, of the complexity and organization in the universe. Rhythmic entrainment can be more or less spontaneous, with the completely spontaneous form being uncontrollable. A balance between the two forms can produce a more robust system, requiring less energy to maintain, whether in physical, biological or social systems. We outline some applications in physics, chemistry, biology, measurement and communication, ending with the especially interesting case of social and economic order. First though, we must introduce some basic principles.*

1. INTRODUCTION

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. The paradigm is a group of jazz percussionists agreeing on a complex musical progression.

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 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 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. 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.

Some symmetry is relic from either earlier undifferentiated conditions and/or deep universal principles, but individual systems are usually individuated through the production of information that distinguishes them from other systems (Collier 1996). 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.

We will outline some applications in physics, chemistry, biology, measurement and communication, ending with the especially interesting case of social and economic order. First though, we must introduce some basic principles. This will be rather brief, but necessary to discuss the examples.

2. REVIEW OF BASIC PRINCIPLES

The notion of information places a central role in our treatment. 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 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.

We therefore first focus 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 (1990) 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. George Spencer Brown (1969) developed a logic of distinctions that has been shown to be equivalent to propositional logic (Banaschewksi 1977, Cull and Franck 1984). Following work by Solomonoff (1964) attempting to develop an information based epistemology that encodes knowledge as minimal descriptions, Kolmogorov (1965, 1968) and Chaitin (1975) showed that information can be expressed as the minimal length of a program that can produce a string that isomorphically maps the yes-no answers to a series of questions that uniquely specify some thing. Basically, following Brown's work, the string is a truth table row that distinguishes the object uniquely, and the information content of the table is the length in bits of the minimal program (of a certain specified type) that can produce the table. This measure of information is equivalent (up to an additive constant) to the probabilistic or combinatorial forms that can be derived from Shannon's work. The connections between information, computation and probability allow a rigorous definition of probability in terms of the compressibility of strings.

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), causation is equivalent to the transfer of the same instance of information (Collier 1999). 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 abstract; the details can be found in the references of (Collier 1999). We turn now to the various kinds of entrainment.

3. VARIETIES OF ENTRAINMENT

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).

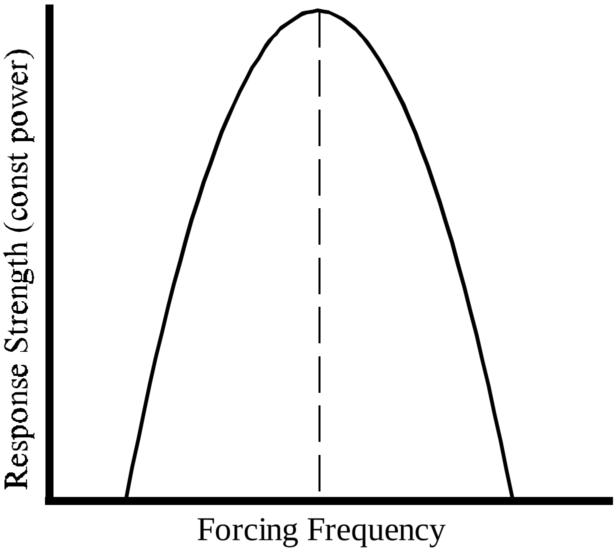

Figure 1 Forced Harmonic Oscillator

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 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.

4. PHYSICS

4.1 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.

4.2 Chemical Systems

We have already mentioned the formation of lipid spheres. 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). Instead we now turn to measurement as another example of entrainment.

5. MEASUREMENT

Measurement is a special form of entrainment in which the measured property drives a special device into a resonance that correlates in a theoretically predictable way with the driving property. We give a couple of examples from geophysics, and then argue that sensation is the most fundamental form of measurement, working on the same principles.

Micro-gravity surveys are often done with a gravimeter, a device that responds to the local force of gravity by moving a delicate spring holding a weight. Absolute measurements are impossible with this device, but the relative force a gravity at different locations can measured very accurately. Basically, the gravitational force twists the spring, the twisting being proportionate to the change in gravitational field strength. This is an example of directly forced entrainment. Absolute measurements are impossible with this device, but the relative force of gravity at different locations can be determined. Magnetic surveys, on the other hand, are done with a device that has an ability to resonate at various frequencies when driven by a force. The magnetic field, much stronger than the energies required to drive the meter into resonance, drives the meter into one of its many possible resonances, designed to be very close together to permit a high degree of accuracy in measurement. In this case, the forcing is indirect, since the meter has its own resonances, one of which is selected by the force of the magnetic field. The two instruments use different principles for measurement, one directly forced, and the other forced indirectly through oscillations.

Sensing is similar to measurement with geophysical instruments, but has some additional interesting properties, both in operation and origin. In operation, energy is passed from the thing sensed that has a form that stimulates the nervous system so as to entrain the form in a way that we can use to form expectations, predictions, and guide actions (though this process is fallible, partly because of possible failings in the sensory system, but more likely at other points in the process.) Possibly, most sensation is more like the gravity meter, directly forced, but in hearing and smell the sensory system has a number of natural resonances, and the forcing is indirect. It has been suggested that both smell and hearing systems are kept normally in a chaotic state, and that the sensation drives the system into one of the infinity of oscillatory states that make up the chaotic state. Although this mechanism is not universally accepted, it would allow very fast sensation, because all the sensory states are already virtually present in the sensory apparatus. A sensory system near to chaos would be almost as effective in response, but would allow only a predetermined set of responses that might be slightly different than the driving sensory impulse. Possibly more subtle phenomena are grasped in the same way, even across sensory modes. In shape and color sensation it is known that there are specific receptors in the eye and brain, but the way these are combined into perceptual images is unknown. Many philosophers (e.g., Harmon 1973) believe judgment is involved in perception. This is surely true at some stage, and if judgement is interpreted loosely enough, perhaps even at an early stage. It is possible, however, that self-organization plays an important role in forming gestalts. These have been largely ignored by contemporary cognitive scientists. Recognized gestalts, such as the examples in textbooks, are probably forced, but new gestalts appear at a new level of organization, and are good candidates for self-organization; they show new order. This process and subsequent selection may be important in creative thought.

Sensory systems, as we have described them, already contain all the possible responses, but they had to originate in some way. This origin was not designed. The most likely explanation is that the underlying structure was malleable, and gradually responded spontaneously to sensory inputs, whose increasing effectiveness was guided by interaction with the environment and by selection. These guiding processes are a sort of forcing that tune the sensory system as it evolves, but the original formation of sensory attractors must have been spontaneous, with information dissipative in the interactive and reproductive and selection processes. Similar mechanisms might be involved in the formation of learned higher order perceptions as well as learned ideas and practices.

One of the more vexing problems of measurement of our day is what happens in Quantum Mechanical system when they interact with measurement (macroscopic devices). In this case the energies involved are very subtle, and we cannot rely on forcing. We speculate a Bohmian style approach in which the guiding wave entrains the measurement device. Since the energy in the wave can be extracted only a half wave length at a time, there are natural limits on this sort of measurement, relative to the size of the properties to be measured. Conjugate values, like momentum and position, which together make up action, the units of the Planck’s constant, cannot be measured entirely independently, since they are entangled in the single wave, and can only be entrained together. This hardly explains the mysteries of Quantum Mechanics, but it does explain the measurement of Quantum systems. The phase information is not available macroscopically (it has no effect on energy), so it cannot be measured. Given that macroscopic values cannot influence phase, the quantum of action places a lower limit on what we can measure. This will be true of any measurement that involves measuring action.

6. MEMES

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.

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. CONCLUSION

The mechanical model persisting since Newton’s time suggests the forced model of entrainment. We have offered an alternative self-organizing model that 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 1999).

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