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Bioenergetics and Biocommunication

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1 Introduction

Organisms are so enigmatic from the thermodynamic point of view that Lord Kelvin, co-inventor of the Second Law of thermodynamics, specifically excluded them from its dominion (Ehrenberg, 1967), while Schrödinger (1944) suggested they feed upon "negative entropy" to free themselves from all the entropy they cannot help producing.

Lord Kelvin was impressed with how organisms seem to have energy at will, whenever and wherever required, and in a perfectly coordinated way. That is at once the problem of bioenergetics -- how organisms can have energy so readily -- and of biocommunication -- how the energy mobilizing activities are organized as a whole. Similarly, Schrödinger alluded to the ability of organisms to use the energy they feed on to build up and maintain their dynamic organization. The intuition of both physicists is that energy and organization are intimately linked.

Schrödinger was reprimanded, by Linus Pauling and others, for using the term ‘negative entropy’, which does not correspond to any rigorous thermodynamic entity (Gnaiger, 1994). However, the idea that open systems can "self-organize" under energy flow became more concrete in the discovery of *dissipative structures* (Prigogine, 1967) that depend on the flow and dissipation of energy, such as the Bénard convection cells and the laser. In both cases, energy input results in a phase transition to global dynamic order in which all the molecules or atoms in the system move coherently. From these and other considerations, I have identified Schrödinger’s "negative entropy" as "stored mobilizable energy in a space-time structured system" (Ho, 1994b, 1995a). In this essay, I show how stored mobilizable energy effectively frees the organism from thermodynamic constraints so that it is poised for rapid and specific intercommunication. In the ideal, the organism is a quantum superposition of coherent activities with instantaneous (nonlocal) noiseless intercommunication throughout the system.

2 Energy storage frees the organism from thermodynamic constraints

2.1 Energy storage and mobilization in living systems

The key to understanding the thermodynamics of the living system is not energy flow or energy dissipation, but energy *storage* under energy flow (Fig. 1). Energy flow is of no consequence unless the energy is trapped and stored within the system where it circulates before being dissipated. A reproducing life cycle, i.e., an organism, arises when the loop of circulating energy closes. At that point, we have a life cycle within which the stored energy is mobilized, remaining stored as it is mobilized, and coupled to the energy flow.

Ji + sk*L*ik**X**k2 (1)

where **J**i is the flow of the ith process (i = 1, 2, 3.....n), **X**k is the kth thermodynamic force (k = 1, 2, 3,.....n), and *L* ik are the proportionality coefficients (where i = k) and coupling coefficients (where i ‘ k), the couplings for which the **X**ks are invariant with time reversal (i.e., velocity reversal) will be symmetrical; in other words,

$$L_{ik} = L_{ki} \quad (2)$$

so long as the **J**s and the **X**s satisfy $Tq = \mathrm{S}\mathbf{J}_i\mathbf{X}_i$ where q is the rate of entropy increase per unit volume (I thank Denbigh (personal communication) for this formulation).

Morowitz' theorem states that the flow of energy through the system from a source to a sink will lead to at least one cycle in the system at steady state, *provided that the energy is trapped and stored within the system* (italics mine). This important theorem captures a key aspect of the steady state, and also implies that the steady state -- at which global balance is maintained -- may harbour nonlinear processes (see Ho, 1993).

Onsager's reciprocity relationship has been extended to the far from equilibrium regime by Rothschild *et al* (1980) for multi-enzyme systems and more recently, by Sewell (1991) for infinite quantum systems. However, the validity and the theoretical basis for the extension of Onsager's reciprocity relationship to biological systems are still under debate (Westerhof and van Dam, 1987). Cortassa *et al* (1991) show that while linear nonequilibrium thermodynamics can describe an autocatalytic system, the matrix of phenomenological coefficients is nonsymmetric. They conclude therefore, that it is the symmetry property (Onsager's reciprocity relationship) and not the linearity of the flow-force relations in the near equilibrium domain that precludes oscillations; and conversely, a system with oscillations cannot at the same time satisfy the symmetry property.

I believe some form of Onsager's reciprocity relationship does hold in living systems if only to account for the ready mobilization of energy on the one hand -- why we can have energy at will -- and on the other hand, for the linear relationships between steady-state flows and conjugate thermodynamic forces outside the range of equilibrium actually observed in many biological systems (Berry *et al*, 1987, and references therein).

According to Rothschild *et al* (1980), linearity in biological processes can arise in enzymes operating near a multidimensional inflection point far away from thermodynamic equilibrium, if some of the rate constants are linked. That is realistic for living systems which are now known to have highly organized flows in the cytoplasmic matrix (Welch, 1985, and references therein). In common with Rothschild *et al* (1981), Sewell shows how Onsager's reciprocity relationship applies to locally linearized *combinations* of forces and flows, which nonetheless behave globally in nonlinear fashion. That is particularly relevant to the living system, where nested compartments and microcompartments ensure that many processes may be operating locally at thermodynamic equilibrium even though the system or subsystem as a whole is far away from equilibrium (Ho, 1995a). Furthermore, as each process is ultimately connected to every other in the metabolic net through catenations of space and time, even if truly symmetrical couplings are localized to a limited number of metabolic/energy transducing junctions, the effects will eventually be shared or delocalized throughout the system, so that symmetry will apply to appropriate *combinations* of forces and flows over a sufficiently macroscopic space-time scale (Sewell, 1991). That is perhaps the most important consideration. As real processes take time, Onsager's reciprocity relationship cannot be true for an arbitrarily short instant, but must apply at a sufficiently macroscopic time interval when overall balance holds.

To summarize, nonlinearity does not preclude symmetry on the appropriate scale, and local linearity does not exclude the possibility for self-organization at a more global level. Hence, the contention that oscillations typical of self-organized systems is incompatible with symmetry properties (Cortassa *et al*, 1991) may be irrelevant when the entire system or sub-system of *balanced* flows and forces is taken into account. This will become clear as we consider the origins of the thermodynamics of the steady state.

2.3 Thermodynamics of the steady state vs thermodynamics of organized complexity

Denbigh (1951) defines the steady state as one in which "the macroscopic parameters, such as temperature, pressure and composition, have time independent values at every point of the system, despite the occurrence of a dissipative process." That is too restrictive to apply to the living system, which has coupled processes spanning the whole gamut of relaxation times and volumes (Ho, 1993). A less restrictive formulation -- one consistent with a "thermodynamics of organized complexity" (Ho, 1994a) -- might be to define the living system, to first approximation, as a *dynamic equilibrium in which the macroscopic parameters, such as temperature, pressure and composition have time-independent values despite the occurrence of dissipative processes*. The present formulation omits the phrase, "at every point of the system". Microscopic homogeneity is not crucial for the formulation of any thermodynamic state, as the thermodynamic parameters are *macroscopic* entities quite independent of the *microscopic* interpretation (Ho, 1993). Like the principle of microscopic reversibility, it is extraneous to the phenomenological laws of thermodynamics (Denbigh, 1951).

The first incursion into the thermodynamics of the steady state was W. Thomson’s (Lord Kelvin) treatment of the thermoelectric effect (see Denbigh, 1951). This involves a circuit in which heat is absorbed and rejected at two junctions (the Peltier heat), and in addition, heat is absorbed and given off (the Thomson heat) due to current flows between two parts of the same metal at different temperatures. Both of these heat effects are reversible, in that they change sign when the direction of the current is reversed. On the other hand, there are two other effects which are not reversible: heat conduction along the wires and dissipation due to the resistance. It is thus impossible to devise a reversible thermoelectric circuit even in principle. Nevertheless, Thomson took the step of assuming that, at steady state, those heat effects that are reversible, i.e., the Peltier heat and Thomson heat balance each other so that no net entropy is generated,

$$DSp + DST = 0$$

On that basis, he derived the well-known relations between the Peltier and Thomson heats and the temperature coefficient of the electromotive force. It was a bold new departure in the application of the Second Law, but one which was subsequently justified by experimental evidence.

Very similar methods were used later by Helmholz in his treatment of the electro-motive force and transport in the concentration cell, where he states clearly that the two irreversible process in the cell, heating and diffusion, are to be disregarded and the Second law to be applied to those parts of the total process which are reversible. Most modern accounts of this system follow the same procedure. A virtual flow of current is supposed to take place across the liquid junction, resulting in a displacement of the ions. The process is taken to be reversible and to generate no net entropy. The justification, according to Guggenheim (cited in Denbigh, 1951), is that the two processes, diffusion and flow of current across the junction, "take place at rates which vary according to different laws" when the composition gradient across the boundary is altered, and so it seems reasonable to suppose that the two processes are merely superposed, and that the one may be ignored when considering the other. Thus, the steady state is treated *as if there were no dissipative processes*, and it is this assumption which is later validated by Onsager's reciprocity relationship.

2.4 The living system is free from immediate thermodynamic constraints

In the same spirit, I propose to treat the living system as a superposition of dissipative irreversible processes and non-dissipative processes, so that Onsager's reciprocity relationship applies only to the latter. In other words, it applies to coupled processes for which the net entropy production is balanced or zero,

$$Sk\ DSk = 0 \quad (3)$$

This will include most living processes because of the ubiquity of coupled *cycles*, for which the *net* entropy production balances out to zero. The principle applies in the smallest unit cycle in the living system -- enzyme catalysis -- on which all energy transduction in the living system is absolutely dependent. Over the past 30 years, Lumry and his coworkers (see Lumry, 1991) have shown convincingly how the flexible enzyme molecule balances out entropy with enthalpy to conserve free energy during catalysis. The organism is, in effect, a closed, self-sufficient energetic domain of cyclic non-dissipative processes coupled to the dissipative processes (Ho, 1995b). In the formalism of conventional thermodynamics, the life cycle, or more precisely, the living system in dynamic equilibrium, consists of all cyclic processes for which the net entropy change is zero, coupled to dissipative processes necessary to keep it going, for which the net entropy change is greater than zero (Fig. 3).

Figure 3. The organism frees itself from the constraints of energy conservation and the second law of thermodynamics.

Consequently, the organism is free from the immediate constraints of energy conservation -- the First Law -- *and* the Second Law of thermodynamics. *There is always energy available within the system, which is mobilized at close to maximum efficiency and over all space-time modes.* This in turn creates the conditions for rapid, sensitive and specific intercommunication throughout the system.

3 The exquisite sensitivity of organisms

3.1 Energy self-sufficiency and sensitivity

One distinguishing feature of the living system is its exquisite sensitivity to weak signals. For example, the eye can detect single photons falling on the retina, and the presence of several molecules of pheromones in the air is sufficient to attract male insects to their mates.

That exquisite sensitivity applies to all levels of ‘information processing’ in the organism, and is the direct consequence of its energy self-sufficiency. No part of the system has to be pushed or pulled into action, nor be subjected to mechanical regulation and control. Instead, coordinated action of all the parts depends on rapid *intercommunication* throughout the system. The organism is a system of "excitable media" (see Goodwin, 1994, 1995), or excitable cells and tissues poised to respond specifically and disproportionately to weak signals because the large amount of energy stored can amplify weak signals into macroscopic actions. It is by virtue of its energy self-sufficiency, therefore, that an organism is a *sentient* being -- a system of sensitive parts all set to intercommunicate, to respond and to act appropriately as a whole to any contingency.

3.2 The polychromatic whole

Evidence for constant intercommunication throughout the living system may already exist in the physiological literature. I refer to ‘deterministic chaos’ which has been used to describe many living functions from the complex, locally unpredictable behaviour of ant colonies (Goodwin, 1994) to unrepeatable patterns of brain activities (Freeman, 1995). A different understanding of the complex activity spectrum of the healthy state is that it is polychromatic (Ho, 1995d), approaching ‘white’ in the ideal, in which all the modes of stored energy are equally represented. It corresponds to the so-called f(l) = const. rule that Fritz Popp (1986) has generalized from the spectrum of light or "biophotons" found to be emitted from all living systems. I have proposed that this polychromatic ideal distribution of stored energy is the state towards which all open systems capable of energy storage naturally evolve (Ho, 1994b). It is a state of both maximum and minimum entropy -- maximum because energy is equally distributed over all space-time modes, and minimum because the modes are coupled together to give, in effect, a single degree of freedom (Popp, 1986; Ho, 1993). In a system with no impedance to energy mobilization, all the modes are intercommunicating and hence all frequencies are represented. But when coupling is imperfect, or when the sub-system, say, the heart, or the brain, is not communicating properly, it falls back on its own modes, leading to impoverishment of its activity spectrum. The living system is necessarily a polychromatic whole, it is full of variegated complexity that nevertheless cohere into a singular being, and that is the ultimate problem of biocommunication that needs to be addressed.

4 The intercommunicating whole

Recent advances in biochemistry, cell biology and genetics are giving us a concrete picture of the organism as an interconnected, intercommunicating whole. It is becoming increasingly clear that living organization cannot be understood in terms of mechanistic controls, nor of endless processings of genetic information.

4.1 A molecular democracy of distributed control

Henrik Kacser (1987) was among the first to realize that in a network, especially one as complicated as the metabolic network, it is unrealistic to think that there could be special enzymes controlling the flow of metabolites under all circumstances. He and a colleague pioneered *metabolic control analysis* to discover how the network is actually regulated. After more than 20 years of investigation by many biochemists and cell biologists, it is now generally acknowledged that so-called ‘control’ is invariably distributed over many enzymes (and metabolites) in the network, and moreover, the distribution of control differs under different conditions. The metabolic network turns out to be a "molecular democracy" of distributed control.

4.2 Long-range energy continua in cells and tissues

Studies over the past 25 years have also revealed that energy mobilization in living systems is achieved by protein or enzyme molecules acting as "flexible molecular energy machines" (Ho, 1995a and references therein) transferring energy directly from the point of release to the point of utilization, without thermalization or dissipation. These direct energy transfers are carried out in collective modes extending from the molecular to the macroscopic domain. The flow of metabolites is channeled coherently at the molecular level, directly from one enzyme to the next in sequence, in multi-enzyme complexes (Welch and Clegg, 1987). At the same time, high voltage electron microscopy and other physical measurement techniques reveal that the cell is more like a ‘solid state’ than the ‘bag of dissolved enzymes’ that generations of biochemists had previously supposed (Clegg, 1984). Not only are almost all enzymes bound to an intricate "microtrabecular lattice", but a large proportion of metabolites as well as water molecules are also structured on the enormous surfaces available. Aqueous channels may be involved in the active transport of solutes within the cell in the way that the blood stream transports metabolites and chemical messengers within the organism (Wheatley and Clegg, 1991).

As Welch and Berry (1985) propose, the whole cell is linked by "long-range energy continua" of mechanical interactions, electric and eletrochemical fluxes and in particular, proton currents that form a "protoneural network", whereby metabolism is regulated instantly and down to minute detail. Cells are in turn interconnected by electrical and other cytoplasmic junctions. And there is increasing evidence that cells and tissues are also linked by electromagnetic phonons and photons (see Popp, Li and Gu, 1992; Ho, 1993; Ho, Popp and Warnke, 1994). As I shall show later, the cell (as well as organism) is not so much a "solid state" as liquid crystalline. Living systems, therefore, possess just the conditions favouring the rapid propagation of influences or ‘information’ in all directions, which are naturally gated in cascades (see Ho, 1993) by the relaxation space-times of the processes involved. These are precisely the conditions that can yield linear flow force relationships in a system globally far from thermodynamic equilibrium (Berry *et al* , 1987). Global phase transitions may often take place, which can be initiated at any point within the system or subsystem. Abrupt, phase-transition like changes in the electrical activities of whole areas of the brain are indeed frequently observed in simultaneous recordings with a large array of electrodes (Freeman, 1995), for which no definite centre(s) of origin can be identified.

4.3 Organism and environment -- a mutual partnership

Biology today remains dominated by the genetic paradigm. The genome is seen as the repository of genetic information controlling the development of the organism, but otherwise insulated from the environment, and passed on unchanged to the next generation except for rare random mutations. The much publicized Human Genome Project is being promoted on that basis (Ho, 1995e). The genetic paradigm has already been fatally undermined at least ten years ago, when a plethora of ‘fluid genome’ processes were first discovered, and many more have come to light since. These processes destabilize and alter genes and genomes in the course of development, some of the genetic changes are so well correlated with the environment that they are referred to as "directed mutations". Many of the genetic changes are passed on to the next generation. As I pointed out at the time, heredity can no longer be seen to reside solely in the DNA passed on from one generation to the next. Instead, the stability and repeatability of development -- which we recognize as heredity -- is distributed in the whole gamut of dynamic feedback interrelationships between organism and environment from the socioecological to the genetic. All of these may leave imprints that are passed on to subsequent generations: as cultural traditions or artefacts, maternal or cytoplasmic effects, gene expression states, as well as genetic (DNA sequence) changes (see Ho, 1986; 1996).

4.4 The distributed organic whole

Thus, the essence of the organic whole is that it is *distributed* throughout its constituent parts, with no centre of control, no governors, no hierarchical levels of line-managers or regulators processing information down the line of command. Instead, pervasive, moment to moment intercommunication throughout the system renders part and whole, local and global completely indistinguishable. The existing mechanistic framework is most inadequate in coming to grips with the organic whole. In the next Section, I shall present an alternative framework based on *coherence*, in particular, on *quantum* coherence.

5 The organism as an autonomous coherent whole

5.1 The coherence of organisms

I mentioned earlier that the living system is necessarily a polychromatic whole -- a variegated complexity that nevertheless cohere into a singular being. The *wholeness* of the organism is the ultimate problem of biocommunication: how to account for the continuity that encompasses the activities of elementary particles and atoms, molecules and cells, tissues and organs all the way to the organism itself (see Joseph Needham, 1936) The problem has never been adequately addressed until Herbert Fröhlich (1968; 1980) presented the first detailed theory of *coherence.* He argued that as organisms are made up of strongly dipolar molecules packed rather densely together (c.f. the ‘solid state’ cell), electric and elastic forces will constantly interact. Metabolic pumping will excite macromolecules such as proteins and nucleic acids as well as cellular membranes (which typically have an enormous electric field of some 10^7 V/m across them). These will start to vibrate and eventually build up into collective modes, or *coherent excitations*, of both phonons and photons extending over macroscopic distances within, and perhaps also outside, the organism.

The emission of electromagnetic radiation from coherent lattice vibrations in a solid-state semi-conductor has recently been experimentally demonstrated for the first time (Dekorsy *et al*, 1995). The possibility that organisms may use electromagnetic radiations to communicate between cells was already entertained by Soviet biologist Gurwitsch (1925) early this century.This hypothesis was revived by Popp and his coworkers in the late 1970s, and there is now a large and rapidly growing literature on "biophotons" believed to be emitted from a coherent photon field (or energy storage field) within the living system (see Popp, Li and Gu, 1992).

In collaboration with Fritz Popp, we have found that a single, brief exposure of synchronously developing early fruitfly embryos to white light results in the re-emission of relatively intense and prolonged flashes of light, some tens of minutes and even hours after the light exposure (Ho *et al*, 1992b). The phenomenon is reminiscent of phase-correlated collective emission, or *superradiance*, in atomic systems, although the time-scale is orders of magnitude longer, perhaps in keeping with the coherence times of organisms. For phase-correlation to build up over the entire population, one must assume that each embryo has a *collective* phase of all its activities, in other words, each embryo must be considered a highly (quantum) coherent domain, despite its multiplicity of activities (Ho, Zhou and Haffegee, 1995).

During the same period of early development, exposure of the embryos to weak static magnetic fields also cause characteristic global transformation of the normal segmental body pattern to helical configurations in the larvae emerging 24 hours later (Ho *et al*, 1992a). As the energies involved are several order of magnitude below the thermal threshold, we conclude that there can be no effect unless the external field is acting on a coherent domain where charges are moving in phase, or where magnetically sensitive liquid crystals are undergoing phase alignment globally (Ho, *et al*, 1994). Liquid crystals may indeed be the material basis of many, if not all aspects of biological organization (Ho *et al*, 1995).

5.2 Organisms as polyphasic liquid crystals

Liquid crystals are phases of matter between the solid and the liquid states, hence the term, *meso* phases (De Gennes, 1974). Liquid crystalline mesophases possess long range orientational order, and often also varying degrees of translational order. In contrast to solid crystals, liquid crystals are mobile and flexible, and above all, highly responsive. They undergo rapid changes in orientation or phase transitions when exposed to electric and magnetic fields (Blinov, 1983) or to changes in temperature, pressure, pH, hydration, and concentrations of inorganic ions (Collings, 1990; Knight, 1993). These properties are ideal for organisms (Gray, 1993; Knight, 1993). Liquid crystals in organisms include all the major constituents of the organism: the amphiphilic lipids of cellular membranes, the DNA in chromosomes, all proteins, especially cytoskeletal proteins, muscle proteins, collagens and proteoglycans of connective tissues. These adopt a multiplicity of meso-phases that may be crucial for biological structure and function at all levels of organization (Ho *et al*, 1995) from channeling metabolites in the cell to pattern determination and the coordinated locomotion of whole organisms.

The importance of liquid crystals for living organization was recognized by Joseph Needham (1936) among others. He suggested that living systems actually *are* liquid crystals, and that many liquid crystalline mesophases may exist in the cell although they cannot then be detected. Indeed, there has been no direct evidence that extensive liquid crystalline mesophases exist in living organisms or in the cytoplasm until our recent discovery of a noninvasive optical technique (Ho and Lawrence, 1993; Ho and Saunders, 1994; Newton, Haffegee and Ho, 1995). This enables us to obtain high resolution and high contrast coloured images of live organisms based on visualizing just the kind of coherent liquid crystalline mesophases which Needham and others had predicted.

The technique amplifies small birefringences typical of biological liquid crystals, enabling us to see the whole living organism down to the phase alignment of the molecules that make up its tissues. Brilliant interference colours are generated, specific for each tissue, dependent on the birefringence of the molecules and their degree of coherent phase alignment. The colours are generated even as the molecules in the tissues are moving about, busily transforming energy. That is possible because visible light vibrates much faster than the molecules can move, so the tissues will appear indistinguishable from static crystals to the light passing through so long as the movements of the constituent molecules are sufficiently coherent. With this imaging technique, one can see that the organism is *thick with activities at every level, coordinated in a continuum from the macroscopic to the molecular*. And that is what the coherence of the organism entails.

These images also bring out another aspect of the wholeness of the organism: all organisms, from protozoa to vertebrates without exception, are polarized along the anteroposterior axis, so that all the colours in different parts of the body are maximum when the anteroposterior axis is appropriately aligned, and they change in concert as the organism is rotated from that position. The anteroposterior axis is the *optical axis* of the whole organism, which is, in effect, a single (uniaxial) crystal. This leaves us in little doubt that the organism is a singular whole, despite the diverse multiplicity and polychromatic nature of its constituent parts.

The tissues not only maintain their crystalline order when they are actively transforming energy, the degree of order seems to *depend* on energy transformation, in that the more active and energetic the organism, the more intensely colorful it is, implying that the molecular motions are all the more coherent (Ho and Saunders, 1994). The coherence of the organism is closely tied up with its energetic status, as argued in the beginning of this essay: energy and organization are intimately linked. The coherent whole is full of energy -- it is a *vibrant* coherent whole.

5.3 Quantum coherence in living organisms

The above considerations and observations convince me that the wholeness of organisms is only fully captured by *quantum* coherence (Ho, 1993). An intuitive way to understand quantum coherence is to think of the ‘I’ that each and every one of us experience of our own being. We know that our body is a multiplicity of organs and tissues, composed of many billions of cells and astronomical numbers of molecules of many different kinds, all capable of working autonomously, and yet somehow cohering into the singular being of our private experience. That is just the stuff of quantum coherence. Quantum coherence does not mean that everybody or every element of the system must be doing the same thing all the time, it is more akin to a grand ballet, or better yet, a very large jazz band where everyone is doing his or her own thing while being perfectly in step and in tune with the whole.

A quantum coherent system maximizes both global cohesion and local freedom (Ho, 1993). This property, technically referred to as *factorizability*, enables the body to be performing all sorts of different *coordinated* functions simultaneously (Ho, 1995b). It also enables *instantaneous (nonlocal) and noiseless intercommunication to take place throughout the system* (Ho 1995f). As I am writing, my digestive system is working independently, my metabolism busily transforming chemical energy in all my cells, putting some away in the longer term stores of fat and glycogen, while converting most of it into readily utilizable forms such as ATP. Similarly, my muscles are keeping in tone and allowing me to work the keyboard, while, hopefully, my neurons are firing in wonderfully coherent patterns in my brain. Nevertheless, if the telephone should ring in the middle of all this, I would turn to pick it up without hesitation.

The importance of factorizability is evoked by the movie character, Dr. Strangelove, portrayed by Peter Sellers as a megalomaniac scientist who wanted to rule the world. He was a wheelchair-bound paraplegiac, who could not speak without raising his arm in the manner of a Nazi salute. That is just the symptom of the loss of factorizability which is the hallmark of quantum coherence.

The coherent organism is, in the ideal, a quantum superposition of activities -- organized according to their characteristic space-times -- each itself coherent, so that it can couple coherently to the rest (Ho, 1995b). It is, in effect a vast array of Fröhlich systems all coupled together. This picture is fully consistent with the earlier proposal that the organism stores energy over all space-time domains each intercommunicating (or coupled) with the rest. It is also consistent with Onsager’s reciprocity relationship or symmetrical coupling between all energy modes. Furthermore, quantum superposition enables the system to maximize its potential degrees of freedom so that the single degree of freedom required for coherent action can be *instantaneously* accessed.

The main implication of quantum coherence for living organization is that, in maximizing both local freedom and global intercommunication, the organism is in a very real sense completely free. Nothing is in control, and yet everything is in control. Thus, it is the failure to transcend the mechanistic framework that makes people persist in enquiring which parts are in control, or issuing instructions or information. These questions are meaningless when one understands what it is to be a coherent, organic whole. An organic whole is an *entangled* whole, where part and whole, global and local are so thoroughly implicated as to be indistinguishable, and where each part is as much in control as it is sensitive and responsive. The challenge for us all is to rethink information processing in the context of the coherent organic whole.

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