Toward a Science of Consciousness
The First Tucson Discussions and Debates

Edited by
Stuart R. Hameroff
Alfred W. Kaszniak
Alwyn C. Scott

29 Water Clusters: Pixels of Life

John G. Watterson

INTRODUCTION

Underlying the phenomenon of consciousness is the concerted, synchronized activity of living cells: the building blocks of the brain and all living tissues. This activity is the result of the ability of cells to sense and respond "meaningfully" to their environment. This ability is a clear sign to us that a cell processes information, that is, the cell is a minicomputer (Conrad 1992). But cells could not act together if they could not act as integral units. I believe that it is this fact, that the cell functions as an entity and not as a jumble of its internal events, that gives it the holistic quality we recognize as "alive." If cells were mere collections of their constituent biochemistry, they could not act in concert, because the overwhelming number and heterogeneity of these internal events would ensure that the probability of any two cells becoming coordinated is next to zero. A worm would not be possible, much less a brain. The living cell (1-μm scale) is a complex system of roughly one part protein to four parts water. Going down in size, we have in the 100 nanometer (10^{-9} meters: "nm") range, integrated subcellular complexes, which when isolated, are able to function as though still in the intact cell; that is, they contain the essential order of living matter. However, at around 5 nm we pass from the world of ordered movement to that of random thermal motion. This is the size range of single protein molecules (that of water being below 1 nm), and represents the mesoscopic range. At this level, we find that intermediate world where independent, coherent, protein mechanisms like enzyme action still operate. Or viewed in the opposite direction, protein is the first step on the upward path from thermal chaos to living matter.

In this presentation, the origin of the "oneness" quality exhibited by cells is traced to order in liquid water at the mesoscopic level. A basic ephemeral order exists in a latent form in water, which manifests itself as dynamic clusters of defined size (Watterson 1991). Under certain conditions these clusters can be given a degree of permanence, giving rise to structures that resemble proteins in size, form, and function. These clusters explain how protein-water interaction produce the extended cooperative three-dimensional system that constitutes living matter, and how, as a consequence,

these individual mesoscopic structures can resonate and transform into a single macroscopic energy quantum.

THE ROLE OF WATER

Ever since that distant time when living matter first appeared, physical conditions on Earth have remained sufficiently stable to ensure the continued existence of liquid water. This fact alone points to a pivotal role for water in the origin and maintenance of life. The liquid state is in general a curious one, because it possesses the properties of both gases and solids, giving flexibility and richness to its molecular dynamics. Although under pressure, liquids adopt a condensed shape as though they are held together internally like solids. This means they exert both pressure and tension simultaneously and thus lie between gases and solids in their properties. Their ability to exist in this seemingly contradictory state is due to the dynamic nature of their molecular structure. The opposing forces of pressure and tension do not cancel one another, but coexist with equal force on separate levels: pressure on the macroscopic and tension on the microscopic level.

Consider a covered beaker containing some liquid (Figure 29. 1). When the contents come to equilibrium, the pressure P and temperature T are constant throughout. We know from Maxwell's Kinetic Theory of Gases, that as we go down in size in the upper gas phase, a unit of volume is reached defined by the Gas Law, which contains an average of one gas molecule. This unit is ideally the volume v_0 where

$$P_0 v_0 = kT \tag{1}$$

and k is Boltzmann's Constant.

Borrowing a useful term from information science, we will call v_0 the "pressure pixel." This concept is an important one for the model developed here, because it takes emphasis away from the actual physical size (cubic
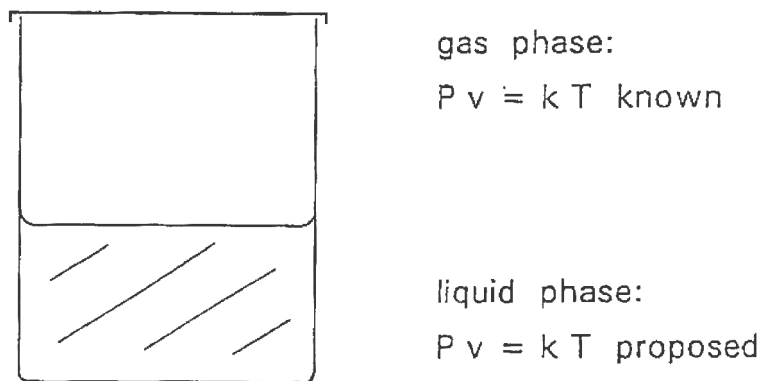

gas phase:

P v = k T known

liquid phase:

P v = k T proposed

Figure 29.1   The Pressure Pixel. The gas and liquid contents of a covered beaker come to mechanical (pressure) and thermal equilibrium. In the gas phase, the size of the pressure pixel is given by the Gas Law. It is argued that the same must apply to the liquid phase, so that pressure has everywhere the same meaning on the molecular level.

nm), and places it on the fact that this volume represents a level in the size hierarchy of physical phenomena. In the top-down direction, a pixel is that region of size where information becomes fuzzy and then lost. Thus v_0 also represents a pixel, since in smaller volumes pressure has no meaning. And this holds whatever the actual size of v_0.

Now P_0, T, and k do not change in value at the interface between the gas and liquid phases; that is, they do not "see" the boundary, so that the properties of the contents are uniform with respect to these parameters throughout the beaker. This raises the question of the meaning of v_0 in the liquid. It is proposed here, that, as in the gas phase, v_0 is the unit of volume that defines the pressure pixel. At room temperature and pressure conditions prevailing in the biosphere, v_0 is about 40 cubic nm, corresponding to a cube with an edge about 11 molecules long containing around 1400 water molecules. We cannot speak meaningfully of pressure in volumes smaller than this basic unit.

The existence of multimolecular structures of this size in liquids is easily understood in terms of the cluster model originally put forward by Frank and Wen (1957). Entities with the size of the pressure pixel do not experience disruptive internal pressure, rather they are held together as a particle by internal tension. In liquids, this tension is mediated by intermolecular interactions, of which the best understood is that in water. It is stronger than in other ordinary liquids because of the H-bond. This bond is due to the tendency of the H atoms of one H_2O molecule to bond with the O atoms of its neighbors. It is known to be responsible for the internal cohesion shown by physical properties of the liquids, as for example, its high melting and boiling points, specific heat, and surface tension. In addition, these interactions are cooperative; that is, their effects are transmitted. Molecules already bonded to others form even stronger new bonds with still other neighbors, and reciprocally, newly formed bonds strengthen existing ones. Thus structuring promotes structuring, so a structure forming process travels like a wave through the liquid (Watterson 1981).

At any instant, a cluster is held together by the cooperative H-bonds like a giant three-dimensional molecule. But this process is opposed by the disordering effect of thermal collisions which limit the extent of structural buildup. As a result, the multimolecular clusters travel through the liquid medium, because their buildup and breakdown are equally fast on-going chemical processes with opposite effect. If we freeze the idealized picture, we see the liquid medium subdivided into a grid of equally sized cubic clusters, each occupying the unit volume v_0. This is the wave-cluster model of liquid structure described more fully elsewhere (Watterson 1987a). Because thermal collisions break down the structure, pressure and cluster size must be inversely related in this picture, just as predicted by the Gas Law.

Even if all the air is pumped out of the beaker, water will evaporate into the gas phase to ensure that the liquid remains under pressure and that Equation 1 still applies. (In this particular case of "no air," P_0 is called the vapor pressure.) It is a long-known fact that if some solute is dissolved in the liquid so that it is no longer a pure solvent (for example, using a salt or

sugar solution as the liquid phase), then the vapor pressure drops. In this new situation, we have pressure P_1, where $P_1 < P_0$, so that in the gas phase

$$P_1 v_1 = kT \qquad (2)$$

where $v_1 > v_0$, that is, there are now fewer molecules in the gas phase.

In the liquid phase however, the water clusters are smaller than in the pure solvent; that is, the solute causes a decrease in the size of the pressure pixel, $v_1 < v_0$ (Watterson 1987b). Therefore, there must be a drop in the value of k according to Equation 2. To understand this change, we recall that the expression kT gives the energy of a vibration, whereby Boltzmann's Constant can be interpreted as the spring constant, and T the variable that indicates which energy level the vibration occupies. Each cluster is supplied with energy at the same level T, whether in the pure solvent (Equation 1) or the solution (Equation 2). But in the case of the solution, the strength of its vibration has been lowered compared with the pure solvent, because the foreign solute molecules disrupt the solvent-solvent interactions, interfering with their geometry and thus breaking down the extent of their cooperative influence, or in other words, the solvent structure becomes degraded by the introduction of unlike molecules. Thus, a lower value of k means that solvent clusters possess lower energy in solutions than in pure solvent under the same conditions of temperature and pressure.

Variation of k opens up a new source of energy available at constant temperature conditions, as is the situation for biological systems. It is the source that explains osmosis and gelation. Proteins also use this source. As opposed to our familiar machines, which operate at high temperatures and pressures, proteins work by tapping into this osmotic form of energy; that is, energy supplied by changes in long-range structures existing on the mesoscopic level. This energy is distinct from the thermal energies derived from random motion on the molecular level below.

According to the classical theory of osmosis however, a solution has a lower free energy than the pure solvent, because the foreign solutes produce increased randomness on the molecular level and the energy change is therefore thermal in nature. This theory predicts that osmosis and gelation cannot occur spontaneously, because, as the pressure increases on a system, so does its free energy, and this is forbidden for a spontaneous change. Yet osmosis and gelation are perhaps the two most important physical processes in biology! Furthermore, randomization has also not been able to explain protein stability—another fundamental problem in biology. This question, discussed next, has been under intensive investigation for 50 years, and still remains unanswered. This fact alone shows us that the statistical mechanical approach will never explain these phenomena. (For a rigorous thermodynamic discussion see Watterson 1995).

PROTEIN STRUCTURE

Proteins are long polymer molecules composed of amino acids linked together in a long chain (average length, about 200 amino acids). But these

chains are not loosely extended, "kicking and screaming" chaotically in a watery solution as predicted by statistical thermodynamics (Cooper 1976). On the contrary, they are folded back and forth in a predetermined way into a compact shape excluding water, which occupies a volume of about 40 cubic nm (Watterson 1991). Thus we can imagine these large molecular solutes as cubes, with an edge dimension in the 3–4 nm range. Because there is a choice of 20 different amino acids as links in the chain, the cubes can have a great variety of internal structure, but for a given purified protein, they are all the same. In other words, in a solution of a purified protein, all the chains are folded identically into a three-dimensional structure unique for that protein, which is stable in water at conditions prevailing in the biosphere.

Because protein size fits that of the pressure pixel, the internal forces are tensile, not compressive. In fact, proteins are known to be held together by an internal network of H-bonds operating between the amino acids, just as is the case in water clusters. The pressure pixel that operates throughout the space filled with water, controls the form of the protein solutes as well. Like water clusters, they too behave like particles. This means that proteins are energetically linked via water structure to gases, where the Gas Law applies. In other words, proteins are related in a fundamental way to other physical particles and are not the chance outcome of a series of highly improbable reactions that occurred in random solutions of heterogeneous chemicals in the distant past, as required by statistical theories of the origin of life.

CYTOPLASMIC TRANSITIONS

The subcellular world is not a disordered solution of proteins, but a structured complex called the cytoplasmic gel. It is the complex as a whole, protein plus water, that constitutes living matter. Therein, water plays the role of an active component and is not just as an inert background solvent (Clegg 1984). The nature of this material cannot be understood in terms of classical theories, which are based on the reductionist assumption that the agent that causes pressure is the water molecule in chaotic motion at the microscopic level. This failure is well illustrated in the case of gelation, the cause of which is thought to lie with the solute molecules alone. In the accepted theory (Flory 1953), long polymer solutes become cross-linked with one another forming a spatious random polymer network. But this picture does not explain why solvent molecules do not flow (some gels are more than 99% water!). Nor can it explain the gelled state of the cell, since in this case the protein solutes are not stretched out and cross-linked throughout its space. Indeed, they are not cross-linked at all. Consequently the theory throws no light on the mechanism underlying this important phenomenon.

In the protein gel, the solute protein molecules are folded into a unique, compact shape occupying a pixel volume. These "permanent water clusters" give solidity to the complex, by inducing the alignment of the spatially compatible water clusters, so that the solute and solvent units stack

together to form a stable, three-dimensional assembly (Figure 29.2). The individual water molecules are not stationary, the clusters are, and consequently water cannot flow as a macroscopic medium.

Further, because of the spatial regularity within the assembly, new entities will emerge at the macroscopic level, as a result of harmonic transitions that occur naturally in wave motion. The swelling of clays provides a sim-
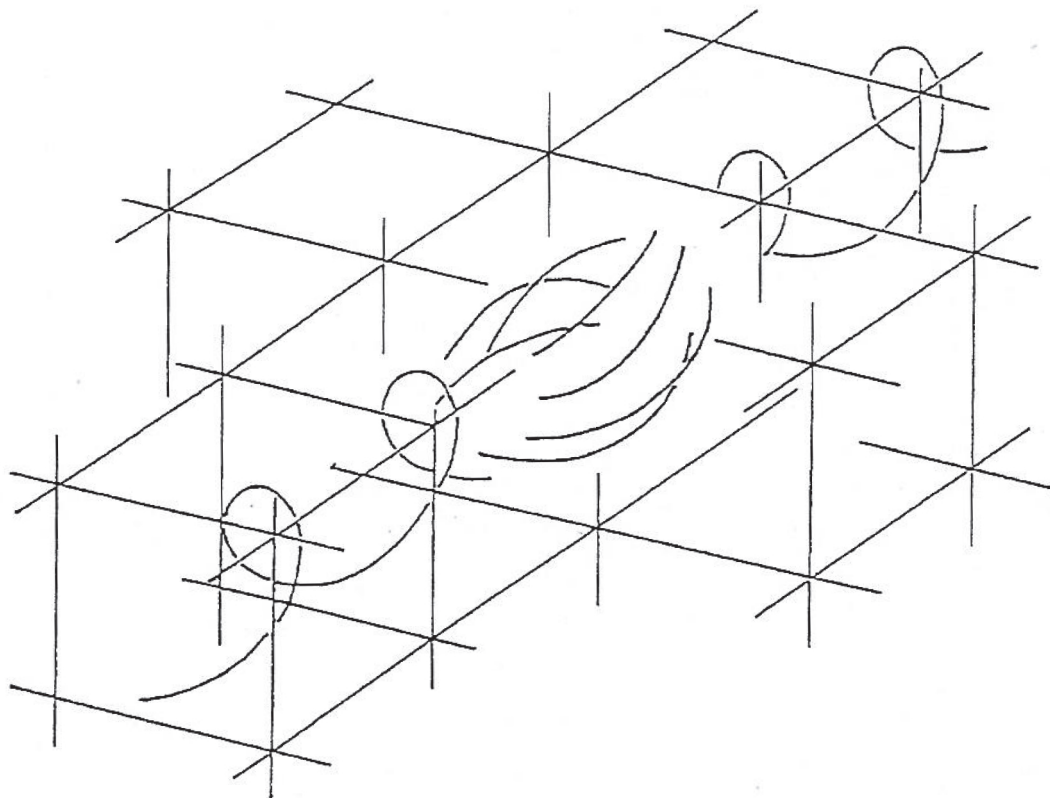

Figure 29.2 The Gel State. Although up to 80% water, this solid-like material is the most important state of matter in the biosphere. As with osmotic phenomena, it is produced by cooperativity between clusters. Protein solutes are like compact cubes with the basic pixel size, 40 nm³. The central cube contains a group of strands representing a protein chain about 200 amino acids long. The strands are each about 10–15 amino acids long and are folded back and forth (the connections at the ends are not shown), so that the chain has an overall form resembling a twisted barrel. The barrel is not rigid, but flexible, because the strands can vibrate with wavelike motion relative to one another. The exact nature of this vibration is determined by the sequence of amino acid links along the neighboring strands, so in this way each individual protein has its own vibrational signature. Small molecules, about the size of a single amino acid, can attach to special binding sites on the protein molecule, usually at the ends of the barrel. (Sometimes they may enter the barrel, for example, the small O_2 molecule binds inside the hemoglobin protein molecule). It is this binding/release step that switches between vibrational modes. The turns of the spiral shown going through the line of surrounding clusters represent how cooperative behavior between clusters in these three-dimensional networks can induce increases in pixel size. This transformation can be likened to a phase transition, since it results here in a "solid" extended structure, that is, a gel. Indeed many protein-water complexes containing tens of separate protein molecules, each with its own function yet acting in coordination with the others, are now well characterized by biochemists.

ple example of this phenomenon. Clay particles are extremely asymmetric in shape, having length and breadth hundreds of thousands of times greater than their thickness (1–2 nm). Familiar clay material is composed of stacks of these microscopically thin sheets, which swell when in contact with water (a problem well known to construction engineers). Water flows spontaneously in between the sheets forcing them apart, even against pressures of hundreds of atmospheres imposed on the stack. As with other examples of such everyday osmotic processes, there is no satisfactory description of molecular mechanism in terms of statistical concepts (Watterson 1991). These classical theories fail again in their explanation, because single water molecules are seen as the agents causing pressure. With this view, we are always faced with the immediate problem of how can molecules under one atmosphere external pressure in the surroundings flow into a region where the pressure is 100 times greater?

As shown in Figure 29.3, the answer lies in the size of the pressure pixel. The introduction of a solid two-dimensional surface into the liquid medium causes an ordering of the clusters. This flat surface induces clusters to take up position forming a packed layer of clusters. Another way of viewing this, is to say the two-dimensional boundary forces a nodal plane in the structure wave. The side-by-side packing of clusters does not mean the immobilization of single water molecules. They move just as in the bulk medium and maintain the wave motion. With the clusters aligned in a regular way, they can interact and induce harmonic transition forming larger and larger clusters. It is now the tension within them that drives the osmotic process by pulling water into the stack parallel to the surfaces (Watterson 1989). This fusion process can produce a cluster as wide and as broad as the particle surface, resulting in a pressure pixel of macroscopic proportions. Pressure no longer operates within this unified layer, since tension has spread laterally throughout the entire region.

Of course, clay is dead material. Its lack of complexity means that it has no information-processing ability. The system lacks the internal flexibility needed for computation, because the pixels are too large and too static. However, the wave mechanism underlying nonlocal, hierarchical effects is well illustrated by its simplicity.

MACROSCOPIC IMPLICATIONS

The mesoscopic entities, water clusters and proteins, lie above the molecular level on the ascending path from microscopic to macroscopic. They are structural elements defined in size by the pressure pixel and emerge from the chaos of thermal motion as a result of cooperative order-disorder interactions between molecules.

Because of the dynamic nature of these opposing interactions, these basic elements appear as a wave, and are no doubt best understood as structural quanta (Kaivarainen 1989). Their wave form means that many such quanta can resonate and fuse to produce a higher-level quantum, if favorable spa-
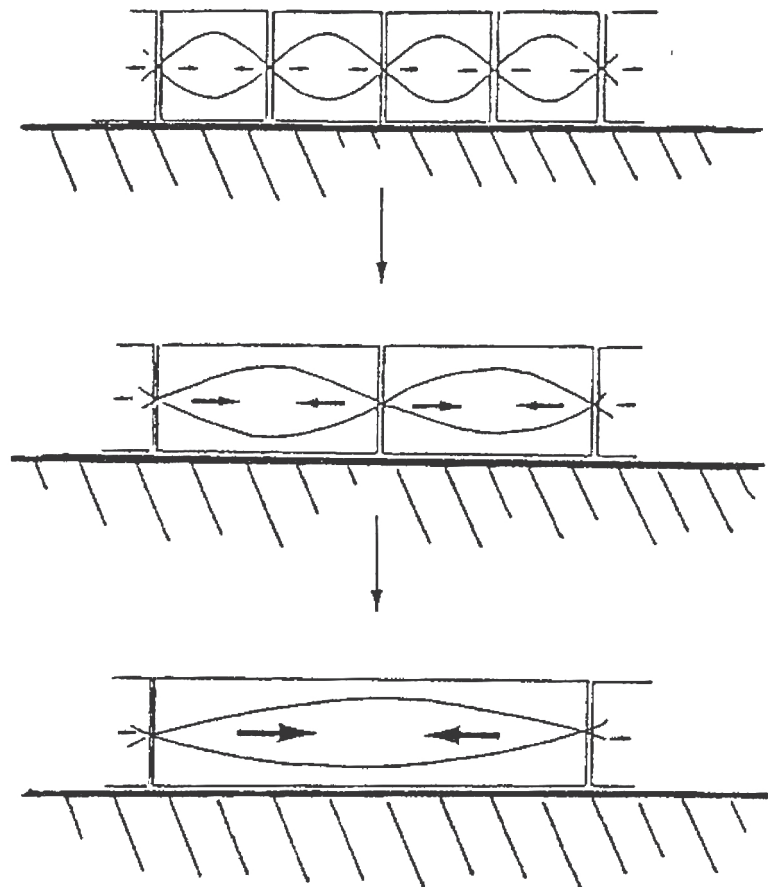
Figure 29.3 The Osmotic Mechanism. Many readers are aware of the swelling of clays and gels as they imbibe water against high opposing pressures. This seemingly contradictory behavior is explained by the cooperativity between water clusters. The presence of an extended two-dimensional surface of the solute aligns clusters, inducing in-phase behavior so the pressure pixel can become as large as the surface. Since tension operates within the pixel, tension can now extend over macroscopic distances even though the material is in the liquid state. The overall three-dimensional effect is an emergent phenomenon that results from the highly parallel arrangement of the surfaces when they are packed on top of each other in a stack.

tial and temporal correlations exist among them. Then many small pixels become one macroscopic one, disruptive pressure becomes unifying tension, and the multicomponent assembly becomes one entity. When such a transition spreads through the whole cytoplasm, the cell acts as one. This macroscopic quantum gives the protein gel its alive quality. This picture is in line with the quantum mechanism that has been proposed to explain long-range coherence in water (Del Giudice et al. 1988) and information processing in the cytoplasm of the nerve axon (Jibu *et al.* 1994).

This phenomenon does not stop at the cell membrane. Although an impermeable barrier to chemical metabolites, the membrane is not a solid, static shell that is separate in substance and function from the cytoplasm. On the contrary, because it is also just 3–4 nm across, its size matches the dimensions of the pixel, making it a natural extension of the protein gel inside (Watterson 1987c). Thus the quanta do not need special gating mech-

anisms to allow them to pass in and out of the cell. One and the same quantum can exist on both sides of the membrane.

By simple extension of this argument, we can ascend to the next hierarchical level, the tissue. Correlations among a population of aligned cells could induce harmonic transitions involving the macroscopic quanta that appear in cells individually as a result of their own internal transitions. Then the whole population would resonate as a single entity. Such may be a mechanism that would help explain the synchronous behavior of brain cells, known to be associated with mental phenomena (Hameroff 1987).

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