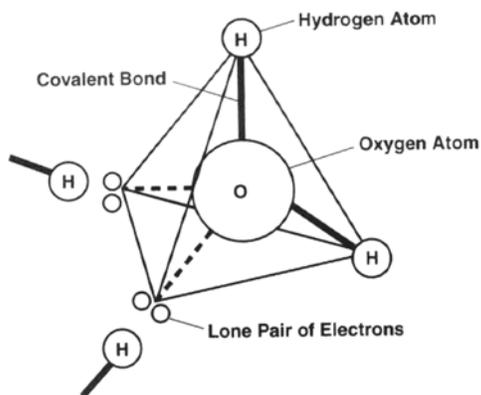


MOLECULAR NETWORK DYNAMICS

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Perhaps the twentieth century's most startling discovery about liquid water is that it functions as a vast interconnected network, rather than as a random collection of independent molecules. Individual water molecules serve as network *elements*, which constitute the building blocks for the fundamental water network. Elements in the water network are connected to one another via magnetic-type linkages known as *hydrogen bonds*. In solid water (ice), each water molecule hydrogen bonds with all four of its nearest neighbors in forming a perfect *tetrahedron*, which is a three-sided pyramid comprising the most basic molecular geometry of water (see Figure 1). As ice melts into liquid water, some of the hydrogen bonds between water molecules are broken (causing the tetrahedron to distort), while the remaining bonds transition to an ultra-dynamic state whereby they are switched as rapidly as a trillion times per second. The dynamics of this unique molecular network are believed to underlie many of water's anomalous properties.

Figure 1. This diagram represents the simplest tetrahedral unit of water's H-bonded network.¹ Two of the four hydrogen atoms comprising the tetrahedron are covalently bonded to the central oxygen atom (forming an individual H₂O molecule), while the remaining two hydrogen atoms (donated by each of two neighboring water molecules) are hydrogen bonded to the oxygen's lone pairs of electrons. Every water molecule in the network is able to act as both a proton donor and a proton acceptor with its nearest neighbors.



NETWORK BEHAVIORS

This frantic switching of hydrogen bonds, which constitutes the underlying dynamism of water's molecular network, permits water to flow and to behave as a liquid even though it retains much of the molecular geometry of a solid. Physical chemists have long modeled liquid water as a space-filling network of individual water molecules, within which all potential hydrogen bonds were described as either unbroken (ON) or broken (OFF).² More recently, scientists have characterized the shuffling (i.e., breaking and forming) of hydrogen bonds comprising liquid water's network as a nonlinear process and, consequently, have been unable to decipher the rules that govern the changing of molecular interconnections. This inability does not imply that the switching rules are haphazard—only that science's observational and mathematical techniques are currently overwhelmed by water's dynamism. Even scientists who study much simpler computer-generated systems have found it difficult to identify switching rules solely by analyzing network patterns and behaviors. Instead, researchers arbitrarily set the switching rules for these artificial systems and then observe corresponding network behaviors.

Whereas network hierarchies within liquid water have only recently been investigated, structural hierarchies are well described. Water exhibits structural self-organization on at least three distinct levels: molecules, clusters of molecules (e.g., hydration envelopes), and clusters of clusters (e.g., micelles). Self-organization implies that water molecules or molecular clusters arrange themselves into increasingly complex states. It is this self-organization that reportedly permits a network of simple interconnected elements, along with their switching rules, to display coherent behaviors.³ Although the primary water network is held together by short-range hydrogen bonds between neighboring molecules, it may either behave as an extensive system with global coherence or as individual smaller regions with local order.⁴ These two behaviors have been classically linked to network patterns displaying disordered or chaotic (i.e., bulk liquid water) and ordered (i.e., water clusters) properties, respectively.

BIOLOGICAL STRUCTURE AND FUNCTION

Molecular biologists originally considered water to be merely an inert solvent within which biomolecules (e.g., proteins and nucleic acids) structured and activated themselves. More recently, water has been perceived as a key structural and functional component of many biomolecules, whose interaction with the surrounding environment is often mediated through *hydration envelopes*, which are immense water networks surrounding the biomolecules.⁵ Water releases its hydrogen bonds with biomolecular components so that protein or DNA assembly may begin. Conformational changes in the biomolecule then restructure both the internal (bound or integral) and external (hydrating) water that, in turn, facilitates more changes in the biomolecule. This process appears to repeat until assembly and folding processes yield a bioactive crystal.

In addition to the structural importance of water in biomolecules, the insertion and removal of water also has profound effects on their functioning. One of the most remarkable functions that proteins perform is that of a biochemical catalyst or *enzyme*, which permits chemical reactions to proceed at rates that are millions of times faster than would occur under ambient conditions. Water appears to play several roles in the functioning of enzymes. First, water molecules located at the interface of the protein-substrate complex often provide the free energy used to actually bind the enzyme to its substrate. Second, water is often excluded from the active site until the moment of catalysis, at which time it is allowed to enter the active site and reconfigure hydrogen bonds (permitting the reaction to proceed). Finally, the enzymes actually structure the water network or networks around them, thus enhancing the rate of catalysis.⁶

In addition to its role as a structural component of biomolecule, water hydrates DNA as it would any other solute in an aqueous solution. It appears that water is most highly ordered adjacent to the DNA molecule and less ordered with each successive hydration envelope. This highly ordered water is sometimes referred to as *vicinal* or biological water.⁶ As was the case for proteins, each subunit of the DNA seems to have its own water network that interacts with other networks and, through successive hydration envelopes, with bulk water. If the geometry of the DNA molecule is contorted, the hydration envelopes and associated geometric clusters

seem to be likewise affected. Similarly, the DNA molecule may contort in response to changes initiated by the water that hydrates it. The reasons for twisting and folding DNA molecules may include stuffing it into chromosomes or unraveling it during transcription and replication.

COMPLEX DYNAMICS

Scientists working with the water *pentamer* (i.e., a pentagonal cluster serving as the basic building block for many large hydration envelopes) observed that water's vibrational states are due to a combination of bending and stretching motions of its bonds. Molecular vibrations are expressed in the units of cycles per second, or *hertz*. While water's covalent bonds vibrate at about 10^{14} hertz (one-hundredth of a picosecond per cycle), its hydrogen bonds vibrate within the lower frequency range of 10^{12} to 10^{13} hertz (one-tenth to one picosecond per cycle). Note that the frequencies of these bond vibrations exceed the time frame (more than one picosecond) that has been measured for the exchange hydrogen bonds in water's bulk liquid network. One *picosecond* equals a time period of one-trillionth of a second (10^{-12} seconds). In addition to the dynamics associated with vibrating and exchanging bonds, water's molecular network performs a number of concurrent activities that have been clocked at both faster and slower rates.

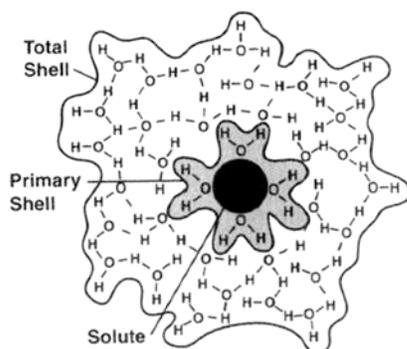
As an example, *ultrafast vibrational energy* is transferred in water on timescales less than one-tenth of a picosecond.⁷ This ultrafast transfer could play a role in liquid water's transporting vibrational energy among certain solutes (e.g., proteins, DNA) and, perhaps, in transferring information within water's local network. Recent spectroscopy studies have suggested that liquid water's network may also function on timescales of less than a *femtosecond* (one-thousandth of a picosecond), which is at least 100 times faster than the ultrafast vibrational energy. Moreover, some of the studies indicate that most molecules in the liquid network form only two (rather than three or four) hydrogen bonds with their neighbors, perhaps creating chains of molecules within a disordered cluster network.⁸ In contrast to these sub-picosecond dynamics, the reorientation of water molecules in a spatially restricted environment (e.g., the interface of a micelle) occurs on the much slower timescale of hundreds to thousands of picoseconds. While further research is required to

substantiate the recent observations, models describing both the structure and dynamics of water's molecular network are rapidly evolving.

SEAWATER

Thus far, the discussion of water's network has dealt with either pure water or dilute aqueous solutions in which solutes comprise only a very small fraction (e.g., less than 0.1%) of the total solution. By contrast, the salts (ions) in seawater account for about 3.5% of the total solution. Unlike the structure of pure water's bulk phases and clusters, the molecular structure of seawater is poorly described and somewhat enigmatic as a result of difficulties associated with employing the investigative techniques that are routinely used to probe the structure of pure water networks. Moreover, the high concentration of ions in seawater is hypothesized to significantly affect the water network itself. As the percentage of water molecules comprising hydration envelopes increases, the network structure of bulk water is compromised (see Figure 2). A salting-out effect is observed at very high ion concentrations, when the interaction between water molecules and ions is weakened enough to permit the formation of salt crystals.

Figure 2. This diagram illustrates the primary and total hydration envelopes surrounding an ionic, or electrically charged, solute.¹ In this case, a positively-charged solute (e.g., a sodium ion in seawater) draws the negatively-charged oxygen atoms of surrounding water molecules toward the center. A solute's effect on the orientation of water molecules in the liquid network is greatest within the primary envelope, or shell, and diminishes as a function of distance from the hydrated ion



The most pertinent changes in the molecular water network that have been observed or hypothesized in transitioning from dilute aqueous solutions to seawater include: [1] the aforementioned ion-ion interactions, [2] overlapping

hydration envelopes in which a single water molecule simultaneously hydrates more than one ion, and [3] varying orientations of the water molecules that comprise ion hydration envelopes.⁹ All of these factors are believed to profoundly affect the structure and dynamics of the water network comprising the world's oceans, which contain 97% of the planetary water. Perhaps scientists will better understand the oceans when the secrets of seawater's molecular network dynamics are more fully revealed.

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