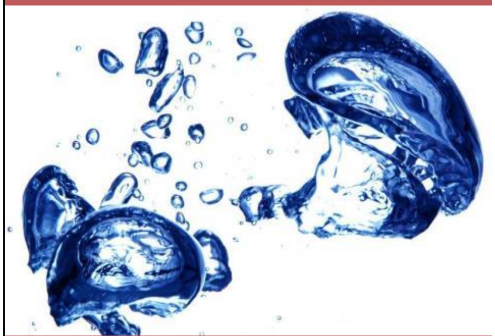

Physical Science of Water

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Introduction

Water is a remarkable substance. If we ourselves were not composed mainly of water, and the substance had only been discovered recently, we might consider it to be the most exotic substance on Earth. It seems ordinary only because we are so familiar with it.

The structures that make up cells are possible because of the structure of water itself. Water allows cells and their components to take shape. It speeds up chemical reactions in cells and water itself or its ions are directly involved in a great many essential biochemical reactions, as either reactants or products.

Before we can talk about the role of water in biology, we have to have a look at the properties that make it so special. This means that we have to understand a little bit about the chemistry and physics of water, the atoms that make up water, and the materials with which it interacts.

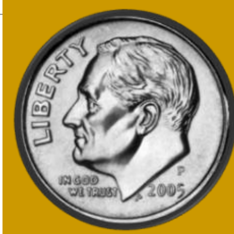
Let's start with an observation. We'll compare water with isopropyl alcohol, otherwise known as rubbing alcohol.

Reference

Watersplash_123rf_3327487_low.jpg

Surface Tension: Demonstration

- Draw a dime-sized circle on a flat piece of waxed paper.
- Place water drop by drop in the center.
- How many drops can you add and stay inside the circle?
- How high off the paper does the drop rise before it collapses?



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Demonstration of Surface Tension

Materials: Waxed paper, marker, water, isopropyl alcohol (or ethanol, methanol, or oil), eyedropper or pipette

Procedure: Draw a circle on the paper the size of a dime. Drop by drop, add water to the center of the circle, trying to keep the growing drop within the confines of the circle. Determine how many drops you can accumulate. Make an estimate of its height. Sooner or later the drop will collapse. How many drops does it take, and how far above the paper does the drop go before it collapses?

Surface Tension: Demonstration

- Draw another circle, same as before.
- Repeat the water drop experiment using isopropyl alcohol, asking the same questions.
- Try as hard as you can to keep the drops confined and to build up the drop so that it grows upward.

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Demonstration, continued

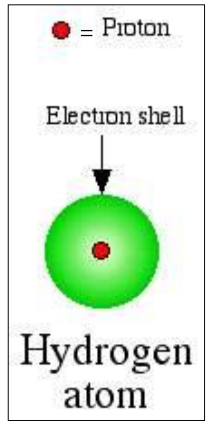
Repeat the experiment, using isopropyl alcohol instead of water. Answer the same questions as before. Can you accumulate even close to the number of drops of alcohol as you did with water? Does the accumulating drop rise above the surface as the water did?

Try to confine the growing drop to one place. Try to "beat" the force of gravity and pile drops on top of one another as you did with water. Can it be done?

Clearly, there is something "special" about the structure of water. It shows a remarkable degree of surface tension, a property that we call cohesion.

Can the Structure of Water Molecules Explain Cohesion?

- Water molecules apparently “stick” to each other.
- Water molecules consist of hydrogen and oxygen (H_2O) .
- Hydrogen atoms have one proton, one electron.
- Oxygen atoms have eight protons, eight electrons.



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Cohesion and VIscosity

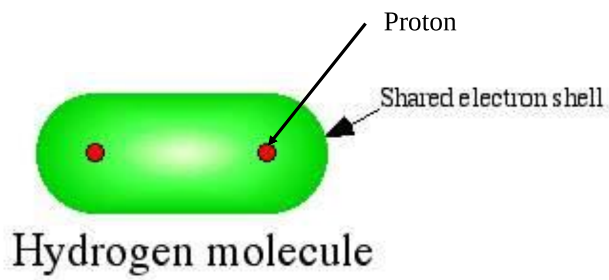
The tendency of a liquid substance to keep its shape, to be “sticky,” or to exhibit cohesion is called viscosity. The viscosity of water makes sense if something about individual water molecules causes them to “stick” to each other. What is special about water, compared to oils and alcohols, that makes it so viscous?

Let’s take a look at the structure of a water molecule. A water molecule consists of one atom of the element oxygen and two atoms of the element hydrogen, each of which is chemically bound to the oxygen atom. All atoms are composed of a positively charged nucleus and one or more negatively charged electrons that orbit the nucleus. A lone hydrogen atom would consist of a single positively charged proton with a single orbiting electron. The nucleus of an oxygen atom contains 8 protons, 8 neutrons, and by itself would have 8 orbiting electrons.

In nature, however, neither hydrogen nor oxygen is commonly found in the form of single atoms.

Hydrogen and Oxygen Gases

- Both elements are gases at room temperature and pressure.
- Both gases are diatomic (H_2 and O_2).



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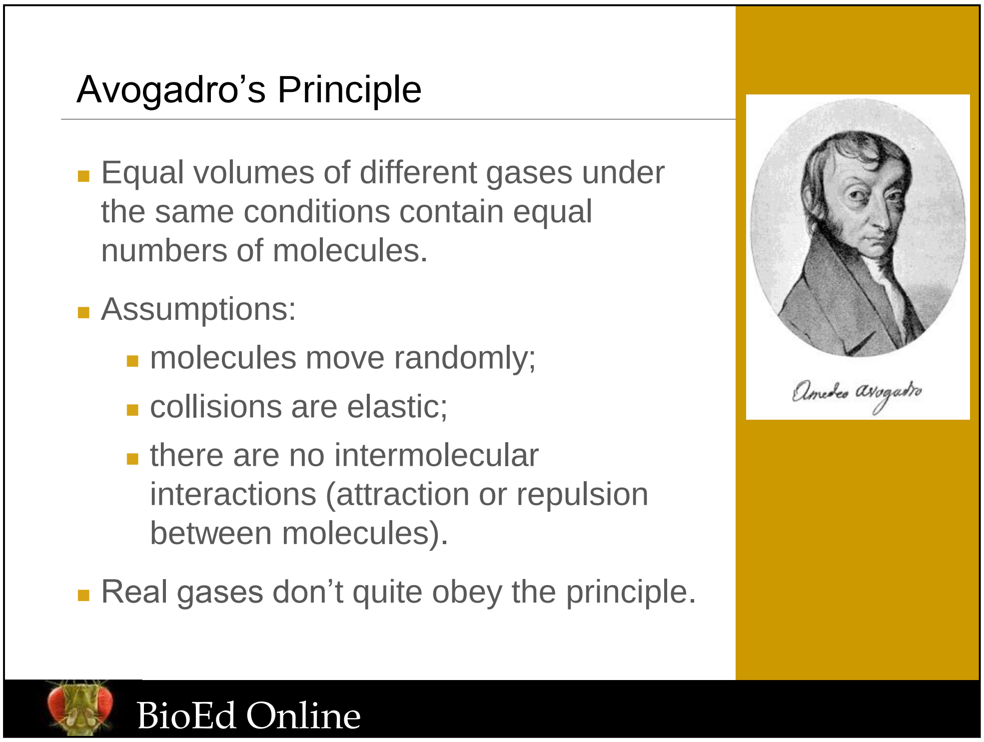
Hydrogen and Oxygen Gases

In their elemental form, both hydrogen and oxygen are gases at standard temperature and pressure. Both gases are diatomic, that is, hydrogen and oxygen are normally found as molecules, each molecule consisting of two identical atoms that share orbiting electrons.

One property of gases is that they fill space. Gases do not stay confined, but will mix with other gases and certainly will fill any vacuum. Why? Understanding the properties of gases was an important pursuit of 19th century chemistry, and it helped lead to the development of modern molecular theory. In turn, we needed to understand the behavior of molecules in order to understand the reasons for the unique properties of water.



Avogadro’s Principle

Amadeo Avogadro is responsible for some of the most important advances in our understanding of the structure and behaviors of gases. However, among most of us he is best known for the number that bears his name. Avogadro’s number (6.02×10^{23}), is the number of atoms in 12 grams of pure carbon. The number, of course, is called the mole. You might be surprised to know that Avogadro never calculated Avogadro’s number. The principles that Avogadro demonstrated or suggested helped advance the theory that explains atoms and molecules, and made the concept of the mole possible.

Avogadro’s Principle states that equal volumes of all gases contain the same number of molecules as long as they are kept under the same conditions. It assumes that there are no interactions among the gas molecules, that is, the molecules all move randomly and when they collide with other molecules they bounce off of each other in what we call an elastic collision. It assumes that the molecules themselves do not interact with each other.

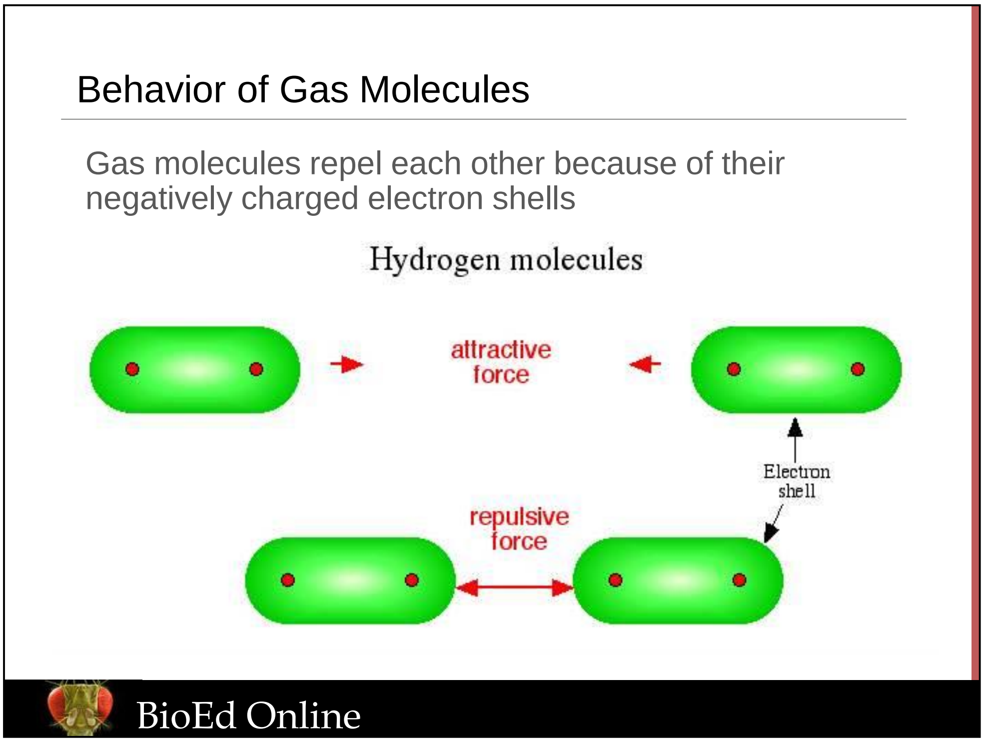
The principle seems to hold most of the time, except when one makes precise measurements using real gases.

References

Avogadro, A. Essay on a Manner of Determining the Relative Masses of the Elementary Molecules of Bodies, and the Proportions in Which They Enter into These Compounds. *Journal de Physique* 73, 58-76 (1811).

Morselli, M. 1984. Amedeo Avogadro, a Scientific Biography. D. Reidel Pub. Co.

Wiki – Avogadro



Behavior of Gas Molecules

Real gases appear to obey Avogadro's Principle up to a point. However, depending on the conditions of the experiment gases do not behave precisely as predicted by the gas laws that were developed on the basis of the work of Avogadro and other 19th and early 20th century chemists. Apparently, the assumptions on which Avogadro's Principle are based are not entirely true.

Gas molecules appear to move randomly because of their high kinetic energy—they move rapidly. However, instead of moving randomly, gas molecules actually attract each other up to some minimum distance. At close distances individual molecules of hydrogen, oxygen, and other gases actually repel each other. Now how can gas molecules attract or repel each other? Such interactions must involve physical forces.

Of the known fundamental forces of nature, two of them apply to the particles that make up atoms, and the other two are gravitational and electromagnetic forces. Molecules have far too little mass to suggest that gravity has anything to do with the forces that make gases spread out or that make water hold together. On the other hand, electromagnetic force can cause objects to repel or attract each other. Perhaps electromagnetic force can explain the behaviors of real gases.

Reference

Resnick, R., D. Halliday, and K.S. Krane. 1992. Physics, Volume One (4th ed.). John Wiley & Sons, Inc.

Demonstration: Electromagnetic Force

- Freshly separated pieces of tape repel each other.
- Contact with moist surfaces discharges the pieces.
- Pieces attached back-to-back and separated attract each other.
- Force of attraction or repulsion increases with decreasing distance between the pieces.
- Gas molecules may repel each other because of their negatively charged electron shells.

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Demonstration: Electromagnetic Force

NOTE: high humidity will prevent these experiments from working—keep the plastic tape in an air conditioned building and/or in a sealed package with desiccant.

Pull two strips of about 10” length from a roll of plastic tape. Try to touch only the ends. Holding each by one end try to bring them together. Do they repel each other?

Pass the length of each hanging strip lightly between your fingers, several times and try again. You should be able to touch the strips together without their repelling each other. It helps if your fingers are moist.

Fold over about an inch of the top of each of the tapes to make a non-sticky tab. Stick the sticky side of one tape to the dry side of the other tape, trying not to rub the tapes too much. You now have a double thick layer, sticky on one side and dry on the other side. Use the tabs to pull them apart rapidly. They should now attract each other instead of repelling each other.

Make a double thick tape with tabs and rapidly pull it apart, as before, and have a friend do the same. Take one strip and bring it close to a strip held by the other person. Does it repel or attract? Try the same strip with the other one held by your friend. The result should be opposite—if it repelled the first strip it will attract the second strip, and vice versa.

The attractive or repulsive forces grow increasingly greater as the distance between the surfaces becomes smaller. Repulsive force between the electron shells of molecules of gas might explain why the molecules repel each other. Why would they attract each other, though?

Reference

"Sticky Electrostatics" [http://amasci.com/emotor/sticky.html]

Ionic Bonds

- The tape experiment demonstrates how ionic bonds are formed.
- NaCl is an ionic compound (Na^+ and Cl^-).
- Positive sodium ions are strongly attracted to negative chloride ions.
- Water molecules are electrically neutral—how can we explain their mutual attraction?

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Ionic Bonds

When dissimilar materials are pressed together they form chemical bonds. The adhesive on plastic tape forms strong enough bonds to hold two pieces together. When pieces of tape are pulled apart the bonds break. Pieces become charged because as the bonds break one surface keeps more electrons than the other surface. The surface with excess electrons carries a negative charge, while the other surface carries a positive charge. In the last experiment, when you peeled the tapes apart you separated dissimilar surfaces, producing one negatively charged tape and one positively charged tape. The two tapes attracted each other because unlike charges attract. Pieces of tape that were charged in the same way bore like charges, and repelled each other. Ionic type chemical bonds work in much the same way.

Sodium metal reacts violently with chlorine gas to form the ionic compound sodium chloride (NaCl). The reaction takes pace because a sodium atom readily gives up an electron and a chlorine atom readily accepts one. Within the molecule the sodium atom is positively charged and the chlorine atom is negatively charged. A type of electrostatic attraction, called an ionic bond, keeps the two atoms together. The unlike charges attract each other very strongly, but ionic bonds are easily broken when the compound is dissolved in water.

The atoms in sodium chloride form ions—a positive sodium ion and a negative chloride ion—when they are dissolved in water. The ions become uniformly distributed in water, suggesting that the electrostatic interaction between ions and water is more influential than the mutual attraction between sodium and chloride ions.

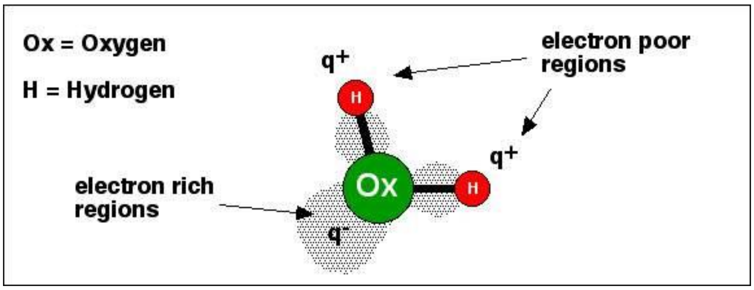
Water molecules contain equal numbers of protons and electrons, so they carry no net charge (the same is true for hydrogen gas). How could there be electrostatic interaction between the sodium and chloride ions and water? The answer lies with the asymmetry of the water molecule.

Reference

Brown, T.L., H.E. LeMay, Jr., and B.E. Bursten. 1991. Chemistry: The Central Science. Prentice-Hall.

Polarity

- Water molecules are electrically neutral.
- Water molecules attract each other—why?
- Each water molecule has polarity.



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Polarity

Water molecules are indeed electrically neutral, meaning that they do not carry any net electrical charge. They do attract both positively and negatively charged ions and each other, and the attraction must involve electrostatic force. How? It turns out that parts of a molecule can be more or less positive than other parts of the very same molecule. Such molecules are said to have polarity.

Oxygen attracts electrons more effectively than does hydrogen. When oxygen and hydrogen are combined in a molecule, the shared electrons spend more time orbiting the oxygen atom than either of the hydrogen atoms. The result is that the oxygen atom carries a partial negative charge and the hydrogen atoms each carry a partial positive charge.

The polarity of water molecules explains why NaCl becomes uniformly dispersed in water. The positive sodium ions are attracted to the negatively charged oxygen atoms and the negative chloride ions are attracted to the positively charged hydrogen atoms in the water molecules. Polarity can also explain how gas molecules attract each other.

Polarity is the basis for several types of interactions among water and other molecules. All of them are essential to the structure and function of cells. One type of interaction is especially important toward our understanding of the properties of water and how it interacts with biologically important molecules. This property, which is the reason that water is cohesive, is called hydrogen bonding.

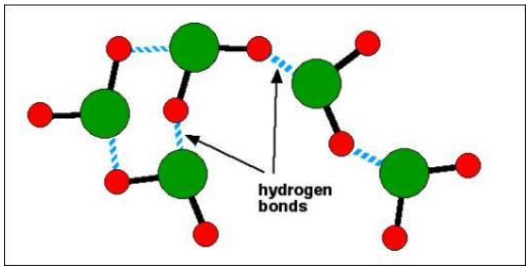
References

Voet, D, J.G. Voet, and C.W. Pratt. 1999. Fundamentals of Biochemistry. John Wiley & Sons., Inc.

Stillinger, F. 1980. Water Revisited. *Science* 209: 451-457.

Hydrogen Bonding

- Polarity permits hydrogen bonding.
- Hydrogen bonds are transient.
- Hydrogen bonds give water a unique structure.



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Hydrogen Bonding

The hydrogen atoms of water molecules form weak temporary bonds with oxygen atoms on nearby water molecules. Hydrogen bonds are somewhat similar to ionic bonds, and are why water molecules "stick" to each other. Because molecules vibrate constantly and because hydrogen bonds are fairly weak, hydrogen bonds are temporary. All the same, hydrogen bonding gives water a unique structure.

The structure of water is so stable that when something else is tossed into water it tends to separate out. That is, the water molecules separate themselves from the intruding molecules. In order to dissolve in water, the new substance must contribute something "special" to the structure of water. It must be able to interact with water molecules to form a new structure that is energetically favorable.

Such is the case with sodium chloride, which fits right into the structure of water. Many biologically important molecules, or portions of them, also fit in well with the structure of water.

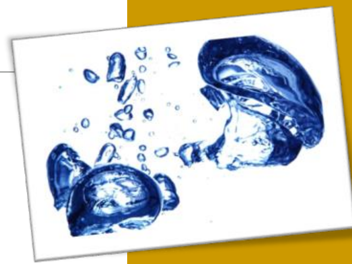
The structure of water, and other properties to be described later, make water so valuable to the structure and function of cells that it is hard to imagine what other liquid might substitute for it. Many of the structures of cells disintegrate in absence of water. Even if they remain somewhat intact, all function is lost.

References

Voet, D, J.G. Voet, and C. W. Pratt. 1999. Fundamentals of Biochemistry. John Wiley & Sons., Inc.

Stillinger, F. 1980. Water Revisited. *Science* 209: 451-457.

Some Advantages of Water's Unique Structure



- Attractive forces of water:
  - capillary action permits water movement in plants.
- Solvent properties:
  - water dissolves acids, bases, salts;
  - water molecules are attracted to other polar molecules.
- Hydrophobic forces:
  - allow structure of cell membranes;
  - contribute to folding of proteins.

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Water's Structure

Water has the property of cohesion because of hydrogen bonding. Water molecules attract each other and it takes energy to separate them. When water evaporates, such as from the leaves of plants, cohesion causes water molecules to be drawn from below. In vascular plants water forms tall columns in which water literally flows uphill. The existence of the tallest living things on the planet, namely trees of 200 feet or more of height, would not be possible without water's cohesive properties.

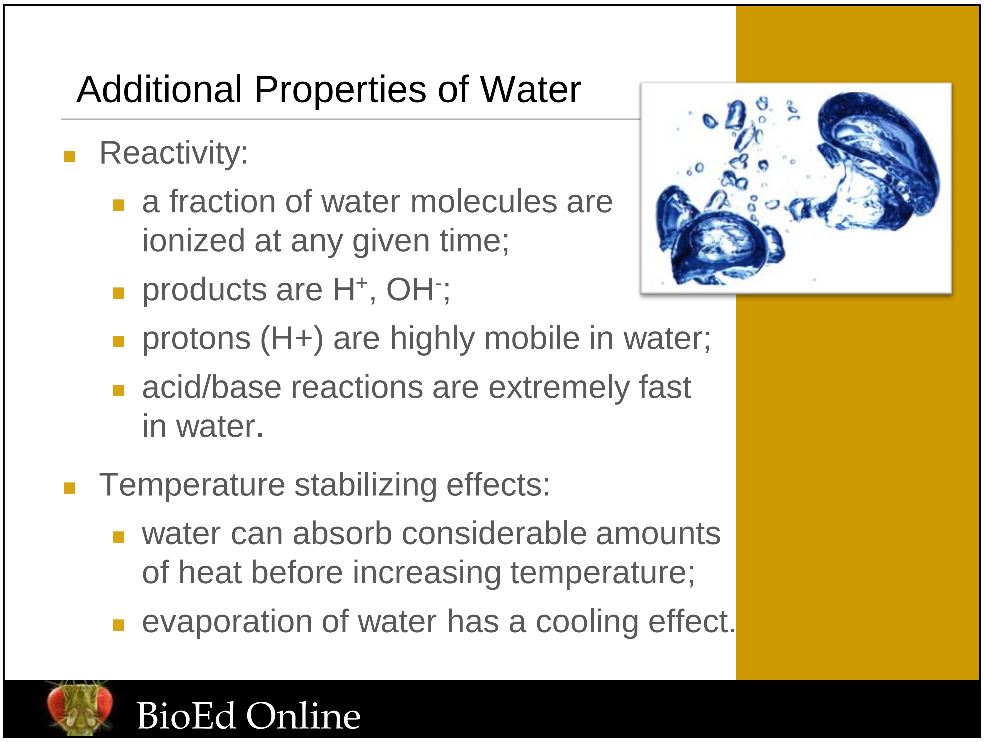
Water has been called the universal solvent. That isn't entirely true, since if it really was a universal solvent it would dissolve any container that we used to try to hold it. It is a very versatile solvent, though. Part of the reason is that it interacts electrostatically with charged molecules, including ions from acids, bases, and salts. It can also dissolve other polar molecules that aren't necessarily charged.

If you try to mix oil and water, they separate out. The same is true for fats and many hormones, and types of proteins. They separate out because they disrupt the structure of water when they are mixed with it. It takes energy to disrupt such structure, and it is the nature of things to stabilize at the lowest energy level attainable. The tendency for substances to avoid water is called hydrophobic force or hydrophobic interaction. Important consequences of hydrophobic interaction are the stable structure of cell membranes and the structure and function of proteins. Molecules that avoid water are called hydrophobic, while molecules that interact readily with water are called hydrophilic ("water-loving").

Let's have a look at an example of how water helps shape proteins and gives them function.

Reference

Starr, C. and R. Taggart. 2004. Biology: The Unity and Diversity of Life. Thompson Learning, Inc.



Additional Properties of Water

The structure of water makes it a very good regulator of temperature. The physical basis of temperature is molecular vibration. The faster molecules vibrate, the hotter they are. When heat is transferred to water it affects the duration and number of hydrogen bonds. That is, some of the energy is absorbed by the structure of water instead of directly causing the water molecules to vibrate faster. Water simply doesn't heat up as quickly nor does it lose heat as quickly as do most other liquids. Enzymes work best within a narrow temperature range, especially in warm blooded organisms. Because the processes occurring within cells produce heat, it is important that water can stabilize the internal temperature. It is also important that water can help dissipate heat.

When water does heat up, hydrogen bonds are broken. Some water molecules escape into the atmosphere as vapor. The process absorbs heat, cooling the remaining liquid. Thus, evaporation of water causes heat loss. Evaporative heat loss is an important mechanism for temperature regulation among many organisms.

At every instant, a portion of water molecules is ionized, that is, some molecules dissociate into hydrogen and hydroxyl ions (H^+ and OH^-). Actually, the positive ions always combine with whole water molecules to produce a hydronium ion (H_3O^+). We use the term hydrogen ion for convenience. Hydrogen ions are very reactive, and water shares them readily. Acid/base reactions take place more rapidly in water than in nearly any other medium.

Water is an important reactant or product of many biochemical reactions. The following is an example of a fundamental process in which water and its components are intimately involved.

Reference

Voet, D, J.G. Voet, and C. W. Pratt. 1999. Fundamentals of Biochemistry. John Wiley & Sons., Inc.