WATER
A SURPRISING MOLECULE

Yasmin Jayathirtha

Why is our search for extra-terrestrial life forms linked to a search for water? Why does ice float in a glass of water? What makes water different from other liquids? In this article, the author uses many everyday observations of water to explore it as a topic that can be studied across classes and disciplines.

Water is the most common liquid we know and we use it without thinking too much about it, except to grumble when it spills, overflows, rain gets in… or to long for when we are thirsty, the tank runs dry or it doesn't rain.

Water plays many roles in our lives, the lives of all organisms, and the planet in general. It is studied by chemists, physicists, biologists and engineers, and research is still being done on it. This is surprising, because it is such a small molecule, such a simple formula - H2O, probably the first that any science student learns.

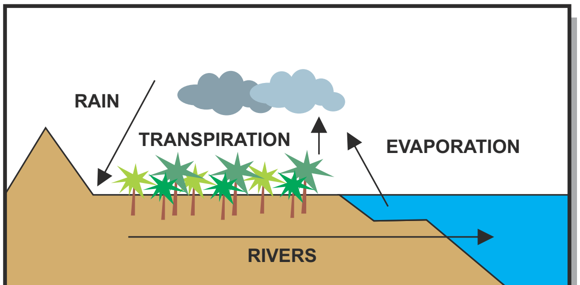
Felix Franks is a British scientist whose work is mainly on the structure and properties of water. He narrates the following anecdote: he was travelling by train to present a lecture on water at a university. He shared his compartment with another scientist who was travelling to the same place for a job interview. On hearing the title of Frank's lecture, he is supposed to have said 'I thought everybody knew the structure of water is H2O'. Franks says 'needless to say, he did not get the job.'

What are all the roles that water plays?

1. It provides an environment for living.
2. It acts as a structural material.
3. It is a very good solvent.
4. It is a transport medium, at large and small scales, for both material and energy.
5. It acts as an insulator.
6. It is a climate moderator.
7. It acts as a coolant.
8. It is a reagent.

There are probably many more uses of water; and many of the roles listed above are linked to each other. We can find numerous examples for all of the above functions of water as we observe life around us.

Let us start with looking at some functions of water that operate at larger scales: we all have some idea of the water cycle, but the sheer volume of water moved around during this process may surprise us.



The Water Cycle
Source: *http://www.teacherplus.org/lets-experiment/the-chemistry-of-water/attachment/le-fig_water*

The seas, rivers, lakes, ponds, little puddles in rocks, and trees, all provide an environment for creatures to live, all over the world, and in all climates. Many small ponds and puddles are teeming with life, very quickly after they form - it is easy to see where the mosquito larvae come from, but what about the fish and the plants - how do they get there? The eggs and the seeds lie there, dry and dehydrated till the rains come, allowing them to germinate and new organisms to grow, providing them with a space to live in- water inside and out.

Why is water essential for life? It provides a medium, in which chemicals dissolve and react; and, also, acts as a reagent to make chemical reactions happen. Can any other compound support life in the same way, not just on Earth, but elsewhere? Xenobiologists (scientists who think about extra-terrestrial life) don't seem to think so. All search for alien life seems to centre on whether water is present elsewhere in the Universe or not. On earth, water is available, and all life has evolved to use it.

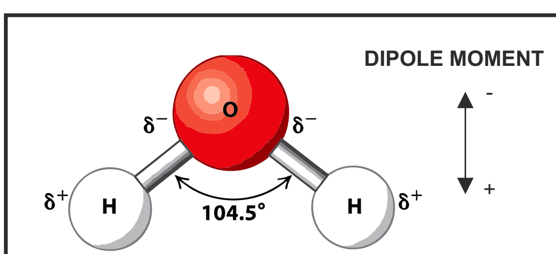
Camels are supposed to carry water in their humps to help them go long distances without drinking. What they do have in their humps is fats. The fats act both as an insulator and as a source of water. Metabolism of food gives out water and that provides part of the water that all organisms require. Metabolising 1 gram of fat gives out more than 1 gram of water. So, the camel gets both energy and water from its hump, and can go many days without eating or drinking. Some scientists have, however, argued that the hump cannot be a source of water to the camel, since taking in oxygen to metabolise the fats in the hump will cause a loss of body water through breathing.

When those of us who are terrestrial, moved from the water to land, we had to evolve ways of getting water, keeping the water in, and making sure that our offspring had water to grow. All groups of organisms solved the problem in different ways, all very marvellous to study as a biologist.

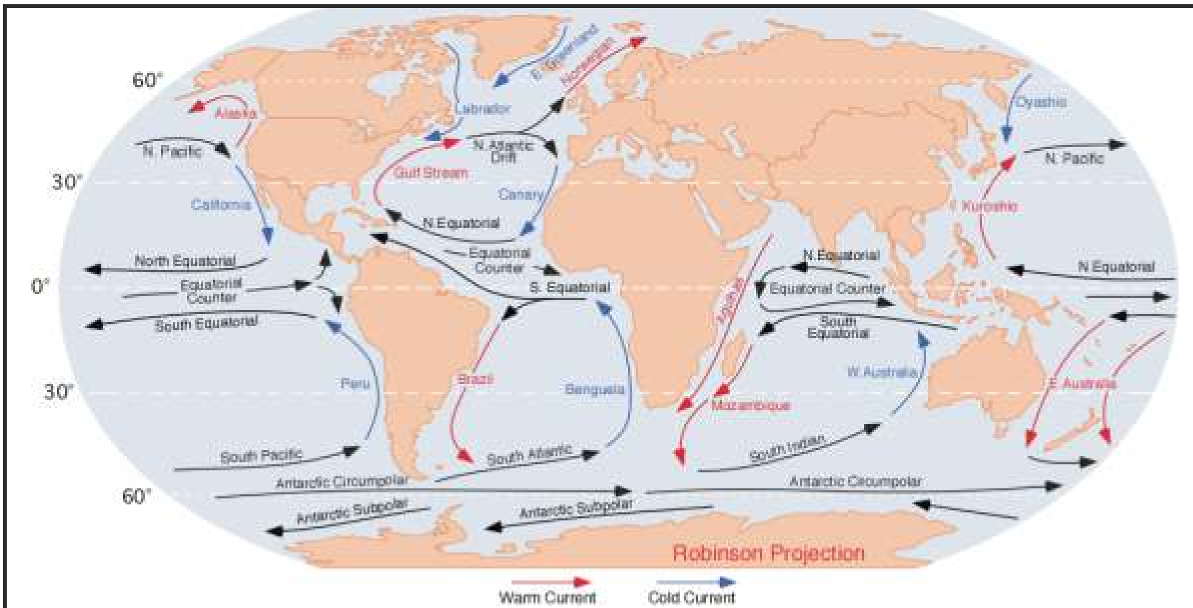
Water falls on to the Earth as rain/snow, dissolving carbon dioxide from the air, and running over land dissolving minerals (notably limestone - $CaCO_3$ through a chemical reaction); finally, either going underground, or into the seas. In the sea, marine creatures use the calcium and carbonate ions, to make shells for themselves.

As water runs over land, it erodes it - both by chemical action, and by physical weathering - shaping landscapes into valleys and gorges. Water is used for large-scale transport through canals, rivers and seas. People sail on seas, using not only seasonal winds, but also seasonal currents. Even big liners, nowadays, use ocean currents to save fuel. These water currents (Gulf stream, El Nino and others) also have important effects on climate.

What is the chemistry of this molecule that makes it so important? The formula of this molecule is H_2O, which means that it has two hydrogen atoms bonded to one oxygen atom (see image below). The atoms share electrons, but because the oxygen atom pulls more strongly on shared electrons than the hydrogen atom can, the molecule has what is called a dipole moment, i.e. one end is slightly positive, and the other, slightly negative. Now, this enables water molecules to attract each other, +ve end to –ve end. Since oxygen has electrons not involved in bonds, the



H2O molecule with dipole moment

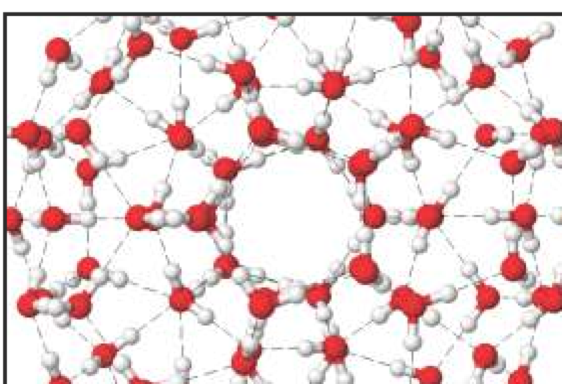


The ocean currents
Source: https://en.wikipedia.org/wiki/Ocean_current . *Public domain*

Dr. Michael Pidwirny (see http://www.physicalgeography.net) - http://blue.utb.edu/paullgj/geog3333/lectures/physgeog.html

+ve H can interact with those electrons, and form a weak bond, called a hydrogen bond. These bonds are weak (about a tenth of the normal bond strength), but they allow water molecules to stick together. This leads to some strange (anomalous) behaviour in water, when compared to other liquids.

Water has a molecular mass of 18. Other compounds of similar masses are all gases at room temperature. That water molecules stick together with hydrogen bonds means that it takes energy to pull the molecules away from each other, and, so, water is a liquid at room temperature. Because the energy required to do this is quite large, it is liquid over a wide range of temperatures: from 0°C to 100°C.



Structure of Liquid water

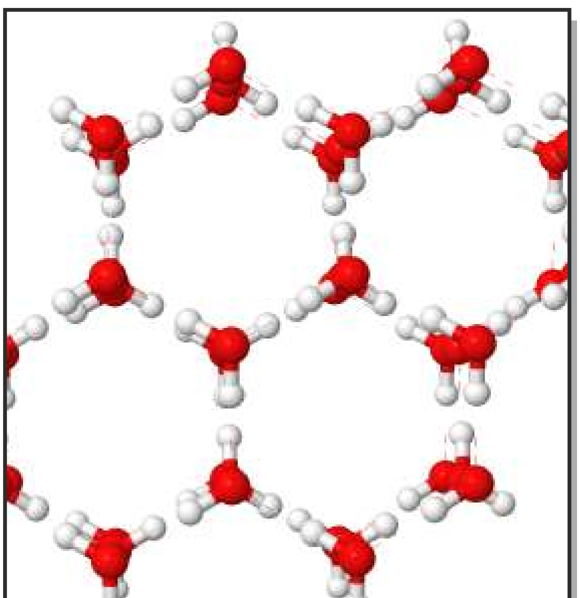
> Most temperature scales use the freezing and boiling points of water as their fixed points. The Celsius scale marks these as 0° and 100° respectively. The Fahrenheit scale takes the lowest temp obtained of an ice/salt mixture as 0°, and puts the boiling point of water at 212°.

Water is the only substance we routinely see in all three states - solid (ice), liquid (water) and gas (vapour or steam).

Some of these properties of water can be explained by the strength of its hydrogen bonds. Water has a very high heat capacity i.e. it takes a lot of energy to raise the temperature of water by 1°C, and a lot of heat is given out when it cools. This means that in living organisms, heat given out by metabolic reactions is absorbed by the water in the body with a very small rise in temperature. Water bodies stabilise temperatures of adjacent landmasses, absorbing heat in summer, and releasing it in winter. Coastal cities and cities near large lakes have far more moderate temperatures than inland ones. The same explanation is true for sea breezes; the land warms up more than the sea during the day, and hot air rises, pulling in the cooler air from over the sea. On a larger scale, seasonally, the same phenomenon is one of reasons for the monsoon patterns in India. On a much smaller scale, swimming pools feel cool on a hot day (the water has not warmed very much) and warm on a cool morning (since it has not cooled too much).

Water has large heats of fusion and vaporisation, i.e. it takes a lot of energy to convert ice at 0° C to water at 0°C and water at 100°C to steam at 100°C. Transpiration in plants and perspiration in animals help them get rid of excess metabolic energy by using it to evaporate water, and cool their bodies.

All these properties of water are explained by the strength of the hydrogen bonds, but water has other properties that are not so easily explained. When liquids are cooled they contract since the molecules that make them have less energy at lower temperatures and are, thus, closer together. This contraction continues till liquids freeze. So, usually, solids are denser than their liquids. As water cools, its density increases, till it reaches 4°C; then begins to decrease. Ice is less dense than liquid water, as is obvious when you see ice floating in your glass. This has profound implications for aquatic life in colder climates. As the weather gets colder, surface water cools down and sinks to the bottom. This process continues till the temperature reaches 4°C and, then, the cooler water stays on top, since it is less dense. When water freezes, it does so from the top, and the rest of the lake for example, stays at ~ 4°C. All the aquatic organisms in the lake can thus survive winters in relative warmth. On the other hand, the expansion when water freezes in cracks within rocks causes physical weathering.



Structure of ice

Many properties of water show this kind of behaviour - not changing continuously with temperature, but showing a minimum or maximum.

1. Heat capacity goes through a minimum at 35°C. Most liquids show a continuous rise.
2. Compressibility - Water is very difficult to compress. Unlike most liquids, water has a minimum at ~46°C. This property allows organisms (both plant and animal) to use water as a skeletal material. Plants are turgid, and wilt when they lose water. Jellyfish, earthworms, and other animals, have water as a skeleton.
3. Speed of sound in water - increases up to 74°C, and then starts to fall.

These are just a few of the properties that show that water behaves differently from most liquids. A lot of current research is focussed on explaining why this may be so.

At room temperatures, water molecules are in loose clusters, held together by hydrogen bonds and exchanging partners rather readily. As the liquid begins to cool, the clusters begin to move into more open-ended arrangements, forming four hydrogen bonds each. So, ice has a more open structure than water, and is less dense and more insulating. As ice melts, about ~ 15% of its H bonds are broken, reducing its volume. As more energy is given to this process, the temperature rises, and more hydrogen bonds are broken, increasing the density of water. But, water molecules move further apart from each other at higher temperatures, decreasing the density of the liquid. The balance of these two opposite processes gives water a maximum density at 4°C. The same interplay between open and closed hydrogen bonded structures give rise to the anomalous structure and properties of water that continue to remain a hot topic of research.

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