Importance of water as a solvent

Why is water a good solvent?

Water is absolutely the most widely used solvent in nature and technology – whether for milk or coffee, rinsing or washing, paper or table salt production, blood, or plant sap. Actually, everyone knows from practical experience that water is a good solvent. But why is this?

Water is a dipole molecule

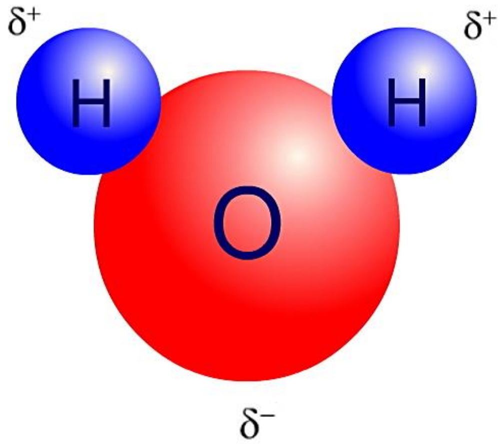

Fig. 1: Water as a dipole molecule

Oxygen (O) and hydrogen (H) form common electron pairs in the compound water (H_2O). The more electronegative oxygen pulls the electrons toward itself. Due to this partial charge displacement, the water molecule becomes polar, meaning it has a negative and a positive end.
This dipolar character is critical for the properties of water as a solvent.
But what substances are dissolved well by which solvents?

Like dissolves like

The following applies to the solubility of solids and liquids in liquids:
Polar substances dissolve best in polar solvents, and nonpolar substances dissolve best in nonpolar solvents.
For example, only very small amounts of long-chain, nonpolar hydrocarbons such as mineral oils dissolve in water (polar solvent). However, they dissolve very well in gasoline, which itself is a fluid, nonpolar hydrocarbon mixture. By contrast, sugar (a carbohydrate), for example, dissolves well in water because carbohydrates are relatively polar due to their numerous OH groups.
The following applies to the solubility of gases in liquids:
Polar gases dissolve best in polar solvents, and nonpolar gases dissolve best in nonpolar solvents. So far there does not seem to be a difference from the solutions with solids and liquids. But unlike the solutions with solids and liquids, the solubility is dependent on pressure, and an increase in temperature decreases the solubility. This behavior results due to the fact that the smallest particles of gases, their atoms and molecules, move at high speed practically independently of each other. Therefore, gas particles constantly enter the liquid at the border between the gas and liquid. On the other hand, gas particles are also constantly leaving the liquid. In other words, gas particles are constantly diffusing through the boundary surface into and out of the liquid.
The rate of gas particles entering the solvent is proportional to the pressure of the gas above the solvent, and the rate of leaving is proportional to the concentration of gas particles in the solvent. The saturation concentration is reached when dynamic equilibrium exists between the two directions of diffusion. The saturation concentration is proportional to the pressure of the gas in the gas compartment.
This is described by Henry’s law:

Saturation concentration = partial pressure x gas solubility

For gas mixtures such as air, partial pressure is understood as the proportion of pressure of the gas being regarded to the total pressure of the gas mixture above the liquid or the solvent.

Another law is important:

Usually, the solubility of gases in liquids decreases as temperature increases.

Also, solids dissolved in the water reduce gas solubility. That's why, for example, oxygen is less soluble in seawater than in freshwater.

Dissolving of gases in water

The different solubility of gases in water is explained by the fact that polar gas particles are held more strongly in the solution than nonpolar gas particles due to interaction with polar water molecules. This effect is amplified even further if a reaction occurs between the dissolved gas particles and the water.

Gas	Solubility
Helium He	0.0015
Hydrogen H_2	0.0016
Nitrogen N_2	0.019
Carbon monoxide CO	0.029
Oxygen O_2	0.0434

Gas	Solubility
Ethane C_2H_6	0.064
Carbon dioxide CO_2	1.688
Sulfur dioxide SO_2	113
Ammoniac NH_3	518
Hydrogen chloride HCl	721

Table 1: Solubility of some gases in water in g/kg water at 20 °C and standard pressure

For instance, the polar gases ammoniac (NH_3) and hydrogen chloride (HCl) dissolve optimally in water. However, reactions occur between these gases and the water: Due to the splitting into H^+ and Cl^-, the aqueous solution of hydrogen chloride is an acid, and due to the formation of NH_4^+ and OH^-, the aqueous solution of ammoniac is a base.
But according to Henry's law, nonpolar gases such as hydrogen, nitrogen, oxygen, and even noble gases such as helium must also dissolve in water. While this is true to a lesser extent, it is still observable.

Dissolving of salts in water

In chemistry, salts are ionic compounds that exist in the solid state and dissolve in water.

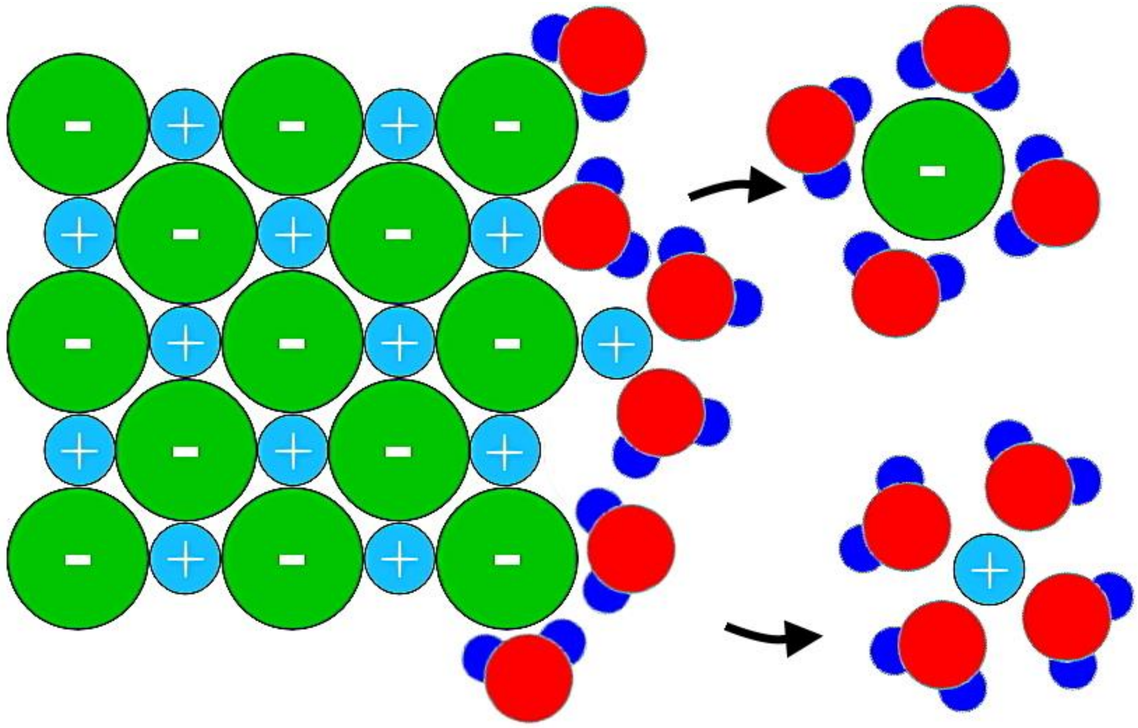

Fig. 2: Process of salts dissolving in water

In the crystal lattice of the salts, the ions are held tightly together by electrostatic interactions. These ions can be dissolved out of the crystal lattice when they interact with the oppositely charged ends of the water dipoles. The separated ions are surrounded by water molecules, and energy is released. This process is called hydration and the released energy is called hydration energy. If this hydration energy is greater than the binding energy of the ions in the crystal lattice, the salt is dissolved (as is the case with table salt, NaCl). By contrast, if the binding energy in the ionic crystal lattice is greater than the hydration energy, the substance is insoluble. For example, that's why the ionic compound Al_2O_3 is insoluble in water and is not a salt.

Life would not exist without the solvent water

The basis of human life and nearly all animal life on Earth is photosynthesis in plants. Glucose, a building block of biomass, is produced from light, water, and carbon dioxide during photosynthesis. Water is not only a starting material of photosynthesis; beyond that, it is a vital solvent for the transport of minerals and other substances. Plants could not grow at all without water as a solvent. In people and animals, many biochemical, enzymatic catalyst reactions also take place in water as the solvent and need water as the educt or release water as a product. For example, hydrolysis reactions are important in digestion, during which the food molecules such as lipids, carbohydrates, and proteins are split.

All substance transport in the body (in blood and lymph) and the removal and excretion of waste products via the kidneys are based on aqueous solutions. By the way, kidneys use reverse osmosis, a principle that is also used in technology, for example, in desalination plants.

Not to be forgotten, the function of nerve and brain cells is based on transmission of impulses via ions, which is not possible without a minimum water content in which the ions are dissolved. However, the story that you become smarter by drinking a lot of water is a typical Internet rumor.

Water as a solvent in the ecosystem Earth

Precipitation cleans the atmosphere

All freshwater on Earth comes ultimately from evaporated water that precipitates over land as snow or rain. You might think that evaporated, thus distilled, water is pure. On the contrary, precipitation gives the air masses a thorough rinsing and cleans dust and soot particles from the atmosphere. In addition, precipitation dissolves gases such as carbon dioxide and oxygen, but also exhaust gases caused by people such as SO_2 and N_2O from vehicles, power plants, and industrial plants. As nice as the cleaning effect of the good solvent water is for the atmosphere, the resulting “acid rain,” for example, can be harmful for vegetation, but also for the production of drinking water.

Pure water does not exist in nature

Thus water does not occur in a pure form in nature, not even as rain. Substantial amounts of mineral salts (for example, alkaline and alkaline earth salts) on the Earth’s surface are dissolved as the rain washes them out of the soil. There are also organic compounds and metabolites from plant metabolism, plus microbes and their metabolic products.
In addition, an immense number of substances from agriculture and industry dissolve in water. With regard to agriculture in particular, dissolved fertilizers (for example, nitrate from synthetic fertilizers and manure) as well as pesticides, fungicides, and herbicides pollute water. This becomes a problem especially when pure drinking water is to be obtained from the polluted ground water and river water. Currently, water that is highly polluted with nitrates cannot be used as drinking water until it has been treated at great expense. As stated in the report from the European Commission on the implementation of the nitrate directive of October 2013, the highest nitrate concentrations in ground water among member states were found in Germany and Malta. (Pollution from industrial waste water is kept within limits in some countries today thanks to stricter legal regulations, but it is still a growing problem in many regions worldwide.)

Gases dissolved in water and their significance for the ecosystem

Oxygen

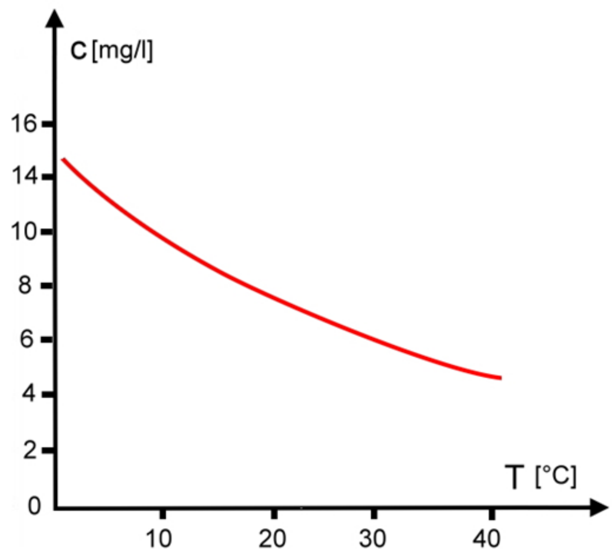

Fig. 3: Solubility of oxygen in water at standard pressure

You can see that oxygen dissolves relatively well in water from the existence of aerobic aquatic animals, meaning animals that breathe oxygen, such as fish and a variety of microbes that require a considerable amount of oxygen. However, the oxygen content of water drops as the water temperature rises. For this reason, fish that need a high oxygen concentration live in cooler waters. These include trout, graylings, and moray eels, which need water with more than 5 milligrams of oxygen per liter (mg/l). Carp and other white fish (bream, tench, catfish) are less demanding and can also survive in waters with an oxygen content of only 3 mg/l. Below 1 mg/l, however, they cannot survive either.

Nitric oxides and ammoniac

Nitric oxides from combustion gases, synthetic fertilizers, and ammoniac from cattle farming can also enter the soil through rain far from their emission sources. This undesirable nitrogen "fertilization" has a harmful effect on many tree species. This causes harm especially to deciduous trees, in particular oak trees. In addition to leaf damage such as yellow and brown coloring, the winter-summer sap balance is disrupted and frost damage increases. In Germany, 88 percent of oaks and 76 percent of beeches were damaged in 2016.

Carbon dioxide

Effect on drinking water

Carbon dioxide (CO_2) dissolves in water far better than oxygen. The resulting carbonic acid breaks down into hydrogen ions (protons, H^+) and hydrogen carbonate ions (bicarbonate, HCO_3^-). This is an acidic reaction, so the pH value of water falls when carbon dioxide is dissolved. This provides a carbon dioxide reserve in the ecosystem: This acidic water containing carbonic acid reacts with calcium carbonate (limestone, $CaCO_3$) to produce calcium bicarbonate ($Ca^{2+}(HCO_3^-)_2$). So, wherever rain falls on soil containing calcium carbonate, the resulting reaction produces calcium bicarbonate in the ground water and spring water. In households, drinking water containing calcium bicarbonate can be bothersome because at higher temperatures, the calcium bicarbonate decomposes again and the calcium carbonate is deposited as sediment (calcification of electric kettles, stainless steel sinks, etc.).

Ocean acidification

In nature, by contrast, the increasing acidification of seawater through contamination with the greenhouse gas CO_2 causes real problems. Due to the increase of carbon dioxide in the atmosphere resulting from human activities, the pH value of seawater has dropped from approx. 8.16 to 8.05 in the past 150 years. Consequently, corals made of calcium carbonate are already starting to die off in many places. In general, all marine organisms that have a calcareous shell are affected, such as mussels. It cannot be ruled out that other marine organisms may also be sensitive to acidification.

Effect on climate change

Carbon dioxide dissolves well in water, which also applies to the Earth's largest water reservoir, the oceans.
Over the last 150 years, CO_2 emissions have increased tremendously due to industrialization and the rise in global population. Initially, relatively little of it remained in the atmosphere. According to Henry's law, as the partial pressure in the atmosphere rose, a lot of CO_2 dissolved in the ocean. The ocean basically acted as a buffer for the carbon dioxide concentration in the atmosphere. However, the increase in global warming and the associated warming of the oceans are now causing the opposite effect: The warm seawater can no longer absorb as much CO_2 as before. More carbon dioxide is remaining in the atmosphere or is entering the atmosphere from the oceans and intensifying the greenhouse effect. This in turn is accelerating climate change. In the 1,000 years before the start of industrialization, the CO_2 concentration in the oceans was approx. 280 ppm. In 2017, it reached a historic record high of over 410 ppm. However, since many other factors also impact climate change, scientists are not certain to what extent and how quickly the release of CO_2 from oceans will affect the CO_2 concentration in the atmosphere.