Water (Science Review)

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Matter, elements, atoms, isotopes, and ions

Matter is anything that has mass and occupies space. Matter is comprised of **elements**, substances with specific chemical properties that cannot be broken down into another substance with different chemical properties. There are 92 naturally-occurring elements and over 20 more that have been created in the laboratory (**Figure 1**). Over 96% of the mass of a typical organism, however, comes from just four elements – oxygen, carbon, hydrogen, and nitrogen.

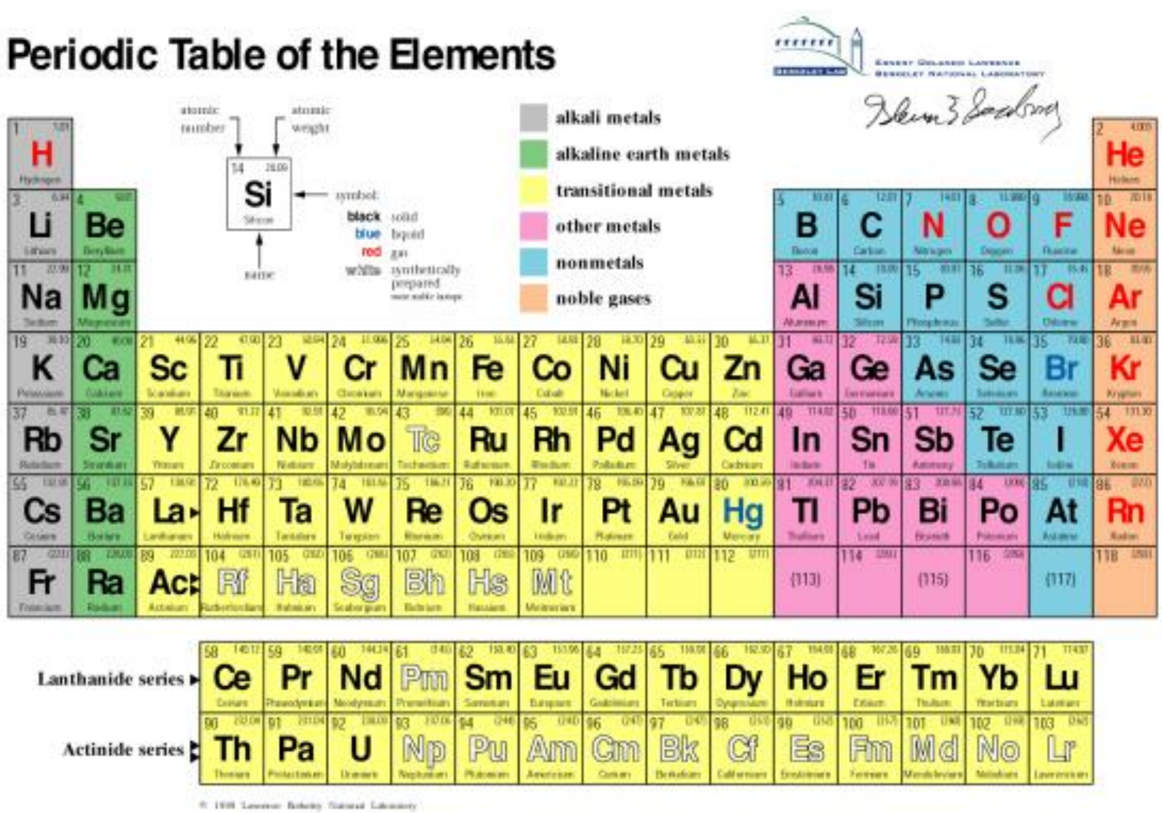

Figure 1: Elements are arranged on the Periodic Table of Elements according to their chemical properties, which are determined by their atomic composition.
Source: http://oxford-labs.com/x-ray-fluorescence/the-periodic-table/

Elements are composed of smaller units called **atoms**, which are the smallest units of an element that maintain the element's chemical properties. Atoms are comprised of a nucleus that contains positively-charged particles called *protons* and uncharged particles called *neutrons*. The nucleus is orbited by tiny, negatively-charged electrons which balance out the positive charge of the nucleus (**Figure 2**). The number of protons in the nucleus affects the atom's chemical properties and defines the element. A nucleus with 6 protons is carbon, one with 20 protons is calcium, and one with 92 protons is uranium.

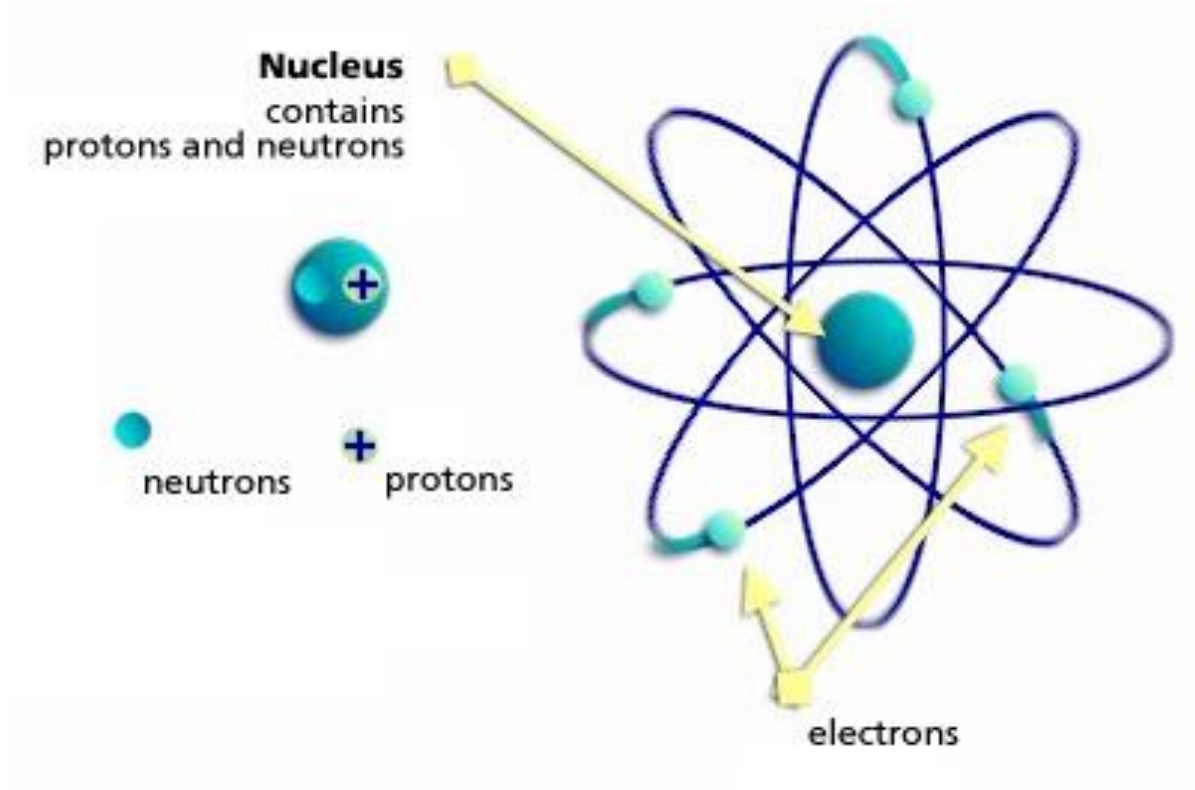

Figure 2: The protons and neutrons in an atom are clustered in the nucleus, which has a positive charge due to the protons. Negatively-charged electrons, equal in number to the positively-charged protons in the nucleus, circle the nucleus. While the electrons are shown as having nice, neat orbital patterns in the figure for conceptual clarity, in reality they circle the nucleus in orbital "clouds"
Source: http://www.gtcceis.anl.gov/guide/rad/index.cfm

While the number of protons in an atom of an element is the same, the number of neutrons in the nucleus can vary. This creates **isotopes** of elements, each with a different atomic mass. Carbon, for example, occurs naturally as the isotopes carbon-12 (6 protons + 6 neutrons), carbon-13 (6 protons + 7 neutrons), and carbon-14 (6 protons + 8 neutrons). Isotopes are useful as they can be used to date ancient objects (such as with carbon-14) or follow the movements of atoms within organisms and ecosystems. The number of electrons can also vary, and atoms can attain a positive or negative electrical charge by gaining or losing electrons to become an **ion**. Charges on ions (or groups of atoms) are indicated by listing the atomic symbol for the element along with a superscript indicating the charge (such as Na^+ for a positively-charged sodium ion that has given up one electron). Some ions lose or gain multiple electrons and attain charges of +2, -2 or more – such as ions of oxygen (O^{2-}) and aluminum (Al^{3+}).

Chemical Bonding

A **molecule** is a combination of two or more atoms joined through **chemical bonding**, which is defined as “a strong attractive force between atoms”. Molecules are written using the atomic symbols for its constituents, with subscripts indicating the number of each atom present. The two hydrogen atoms and one oxygen atom that comprise a water molecule are therefore written as H_2O. If the molecule contains atoms of more than one element, it is called a **compound**. Carbon dioxide (CO_2) and ammonia (NH_3) are compounds; nitrogen gas (N_2) is not. Most molecules are incredibly small. For example, one-billionth of a drop of water contains about two trillion water molecules.

Atoms and molecules combine with each other through ionic bonds, covalent bonds, and hydrogen bonds (**Figure 3**).

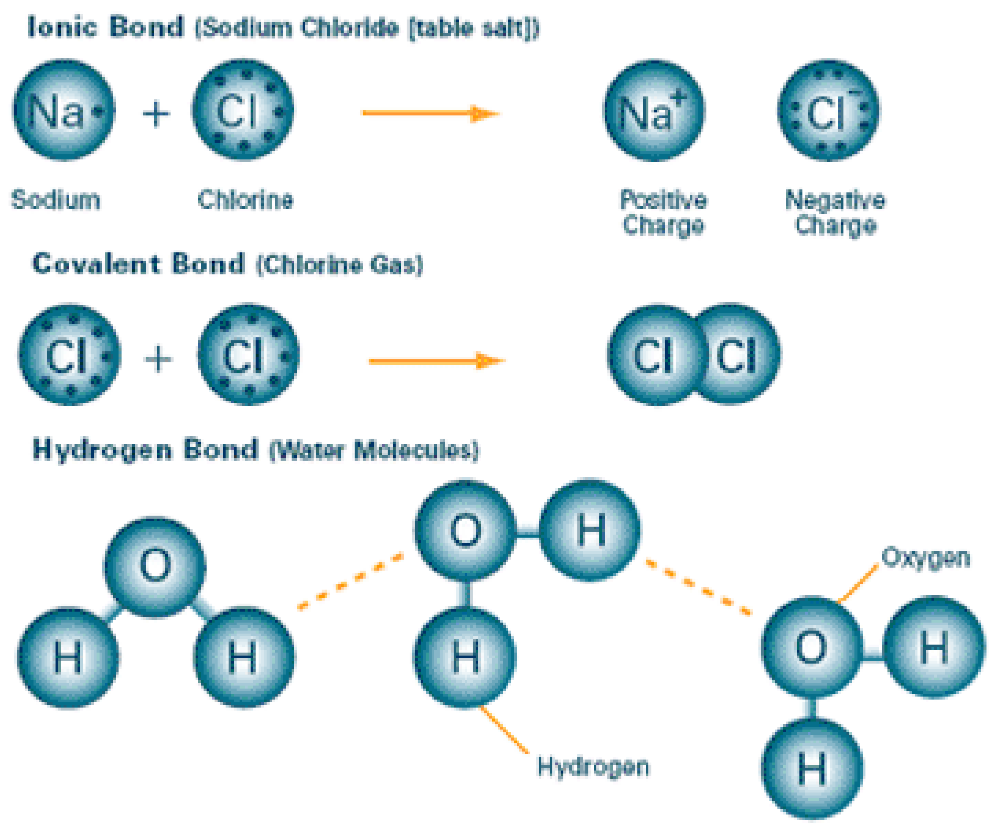

Figure 3: Atoms and molecules combine through the attraction of ions (ionic bonds), the sharing of electrons (covalent bonds), and the attraction of partial charged portions of molecules (hydrogen bonds).
Source: http://www.amasci.net/knowledge/chemical-bonds.php?lang=eng

Electrically-charged atoms of differing charge bind with one another in **ionic bonds**. A crystal of table salt, sodium chloride (NaCl), is held together by ionic bonds between the positively charged sodium ions (Na^+) and the negatively charged chloride ions (Cl^-). The atoms form a three-dimensional lattice in which each sodium atom is bonded to four chlorine atoms and vice-versa. The compound has an overall neutral charge due to equal numbers of positively and negatively charged ions.

Atoms that lack an electrical charge combine by sharing electrons in **covalent bonds**. The two atoms move very close to one another, causing their electrons to orbit both atoms. This provides the two atoms greater atomic stability than when they were separate, leading to a strong bond. The number of covalent bonds needed by an atom to reach the "stable" state depends on its number of electrons, and so varies by element. Hydrogen needs one covalent bond to reach the stable state, oxygen needs two bonds, and carbon four bonds.

Not all atoms play fair when sharing electrons in covalent bonds. Sometimes one of the two atoms "pulls" the electron more strongly, and causes it to spend more time closer to it than the other atom. We saw that a water molecule is one example, as the oxygen atom has a greater attraction for the shared electrons than the hydrogen atoms, resulting in partial positive and negative charges on different parts of the molecule and the ability to form **hydrogen bonds** with charged atoms and molecules. Hydrogen bonds are weaker than covalent bonds, but are common in biological systems. They bind constituents of proteins, help hold together the double-helix structure of DNA, and are involved in many enzymatic reactions.

Changes in Matter & the Law of Conservation of Matter

Matter on Earth typically exists as solids, liquids, and gases. When a substance changes state (liquid, solid, or gas) it has undergone a **physical change**. The molecules have not changed chemical composition, just the form the element or molecule takes on differs. The atoms in a solid are very orderly arranged, liquids somewhat less orderly, and gases even less. This is what gives each of these physical states their particular characteristics. So while water can exist as ice (solid), liquid water (liquid), or water vapor (gas), it is still comprised of water molecules. The molecules are simply moving around and bonding in different ways in the three states and that gives them their different properties. The hydrogen bonds between water molecules in ice are solid, so when you fall on ice the bonds don't come apart easily and you come away with an aching back. The water molecules in liquid water are constantly forming and breaking hydrogen bonds, so your jump into a pool and slice through these bonds with far less resistance. Water molecules in a gaseous form are moving so rapidly that they do not form bonds with other water molecules for any appreciable length of time. Hence, you can wave your hand back and forth through water vapor and encounter no perceivable resistance.

While we're used to seeing matter as solid, liquid or gas, there is a fourth state of matter called *plasma* - a gaseous mixture of charged atoms with an overall neutral charge due to equal numbers of positive and negatively charged ions. Such substances are sometimes referred to as "ionized gases", and they make up 99% of the matter in the visible universe due to the large amounts of plasma in stars. Plasma occurs naturally on Earth during lightning events, but otherwise is rare. Plasmas are artificially created by humans and used in a number of consumer and industrial applications, such as plasma TVs, lasers, and lighting.

Chemical change occurs when one or more different kinds of matter are changed into one or more new kinds of matter. When hydrogen and oxygen are combined to make water, a chemical change has occurred. When water is split into hydrogen and oxygen, a chemical change has occurred. Any time elements and molecules combine or split to form something new, a chemical change has occurred. When a chemical change occurs, atoms are not created or destroyed – they are simply rearranged. This idea is formalized in the **Law of Conservation of Matter** which states that while chemical changes create new substances, matter is not created or destroyed in the process. This means the atoms in your body now have likely been cycling on this planet for billions of years and may have been part of ancient organisms before finding their way into your tissues. Another implication of this law is that we cannot ever truly throw things "away". When we generate garbage, we can't simply destroy the atoms and solve our disposal problems. When we produce nuclear waste or toxic chemicals we can't simply make that matter vanish. We can store them away and take care to see that they don't reenter the environment, but the matter that comprises them doesn't disappear.