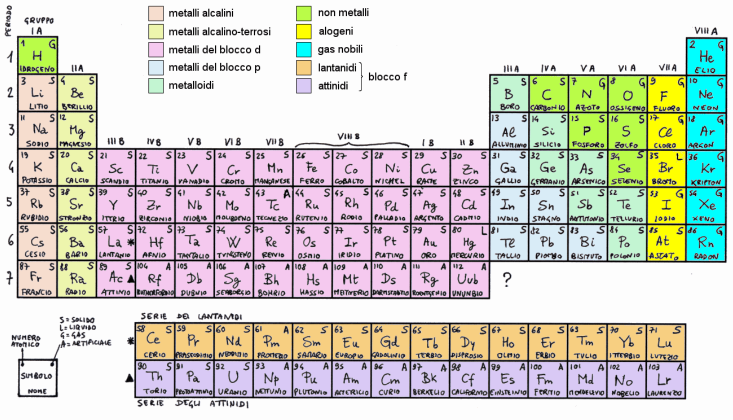
The chemical components of a cell

Cells are made from a few types of atoms.

Even if there are 92 naturally occurring elements , living organisms are made of only a small selection of these elements, four of which:

- Carbon (C)
- Hydrogen (H)
- Nitrogen (N)
- Oxygen (O)

. make up 96.5% of an organism's weight.



Main elements in the human body:

Oxygen (65%)

Carbon (18%)

Hydrogen (10%)

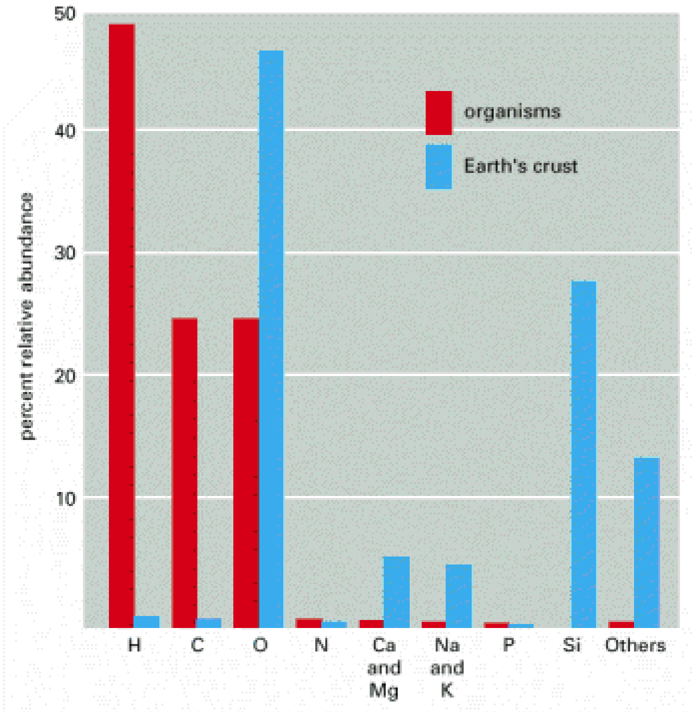
Nitrogen (3%)

Calcium (1.5%)

Phosphorus (1.0%)

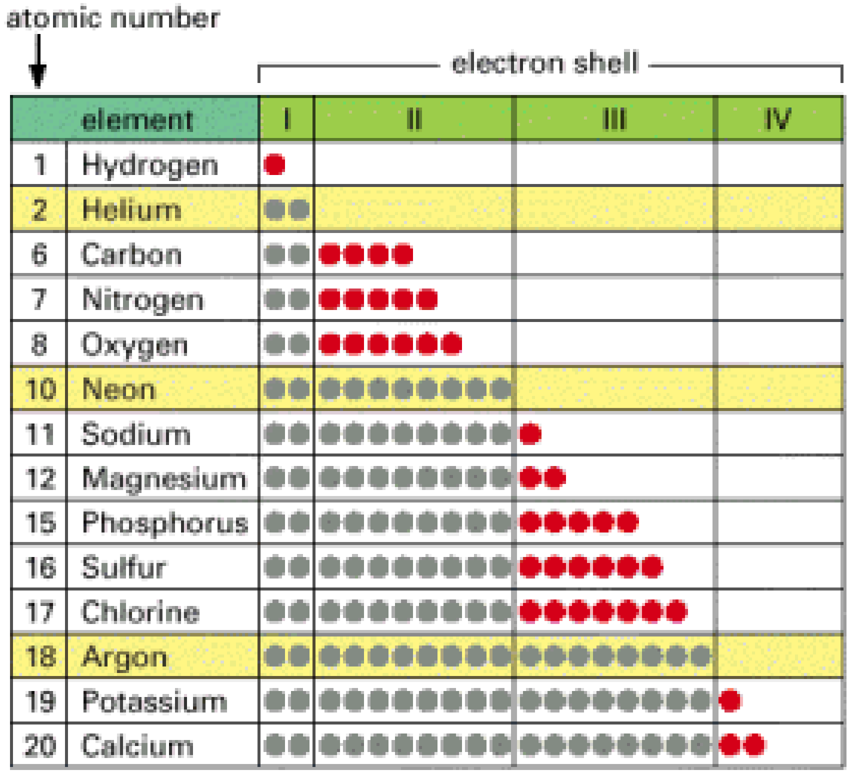
Potassium (0.35%)

The chemical components of a cell



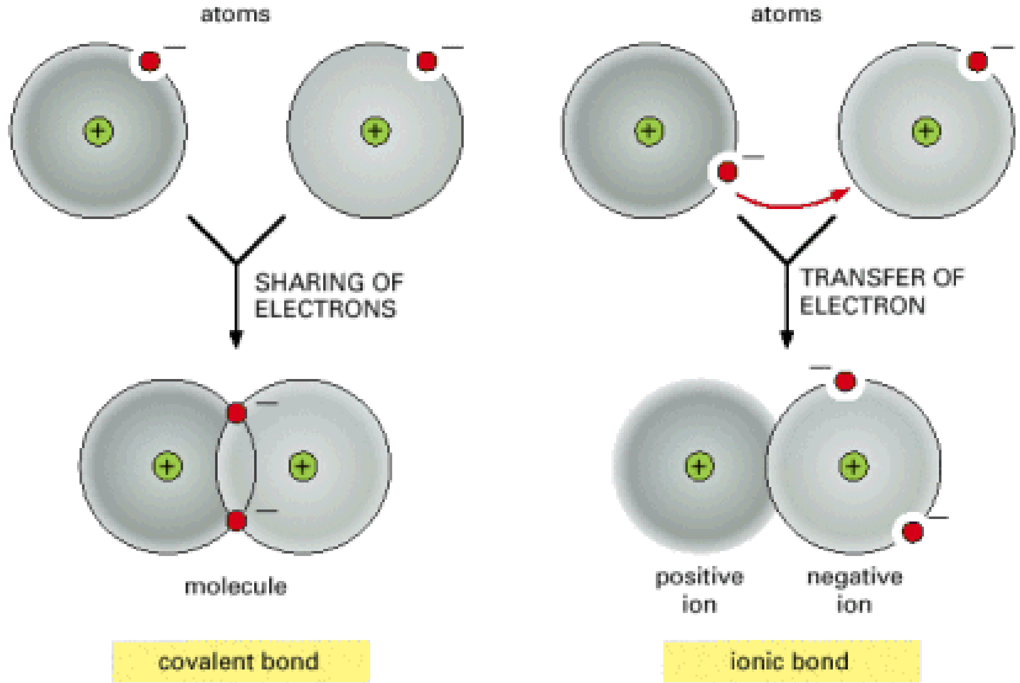
The abundances of some chemical elements in the nonliving world (the Earth's crust) compared with their abundances in the tissues of an animal. The abundance of each element is expressed as a percentage of the total number of atoms present in the sample. Nearly 50% of the atoms in a living organism are hydrogen atoms. The survey here excludes mineralized tissues such as bone and teeth, as they contain large amounts of inorganic salts of calcium and phosphorus. The relative abundance of elements is similar in all living organisms.

The outermost electrons determine how atoms interact (1)



All the elements commonly found in living organisms have unfilled outermost shells and can thus participate in chemical reactions with other atoms. For comparison, some elements that have only filled shells are shown; these are chemically unreactive.

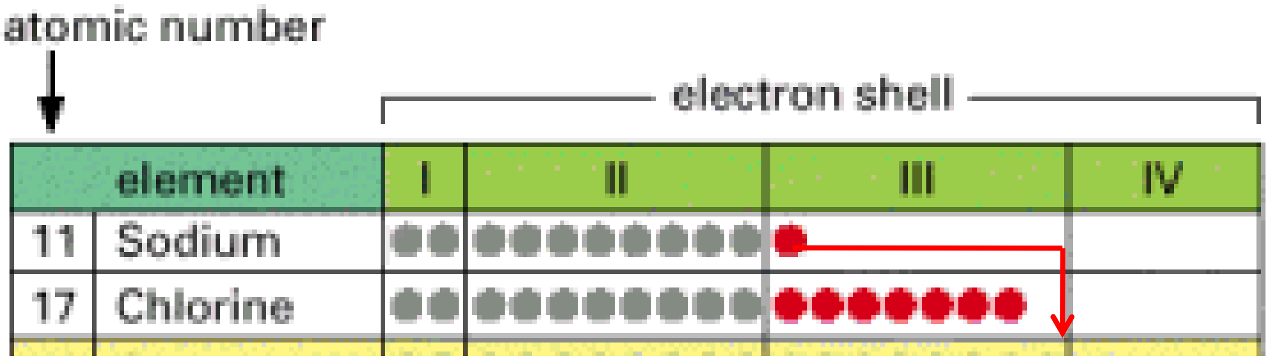
The outermost electrons determine how atoms interact (2)



Atoms can attain a more stable arrangement of electrons in their outermost shell by interacting with one another. An ionic bond is formed when electrons are transferred from one atom to the other. A covalent bond is formed when electrons are shared between atoms. Often, covalent bonds form with a partial transfer (unequal sharing of electrons), resulting in a polar covalent bond.

Ionic bonds (1)

They are most likely to be formed by atoms that have just one or two electrons in addition to a filled outer shell or that are just one or two electrons short of acquiring a filled outer shell. They can often reach a completely filled outer electron shell by transferring electrons to or from another atom than by sharing electrons.



Sodium becames a positive ion (cation): Na^{+}
Chlorine becames a negative ion (anion): Cl^{-}

Because of their opposite charges Na^{+} and Cl^{-}
are attracted to each other and pack in a precise 3D array (reticulum).

Ionic bonds are one type of noncovalent bonds.

Ionic bonds (2)

They form between two charged atoms in two main steps.

1) The electron transfer
2) The electrostatic attraction between the two ions

In the case of NaCl
The formation of the two ions (step1) requires:
- the energy that is necessary for ionizing the Na atom +
- the energy gain by the Cl atom (electron affinity)

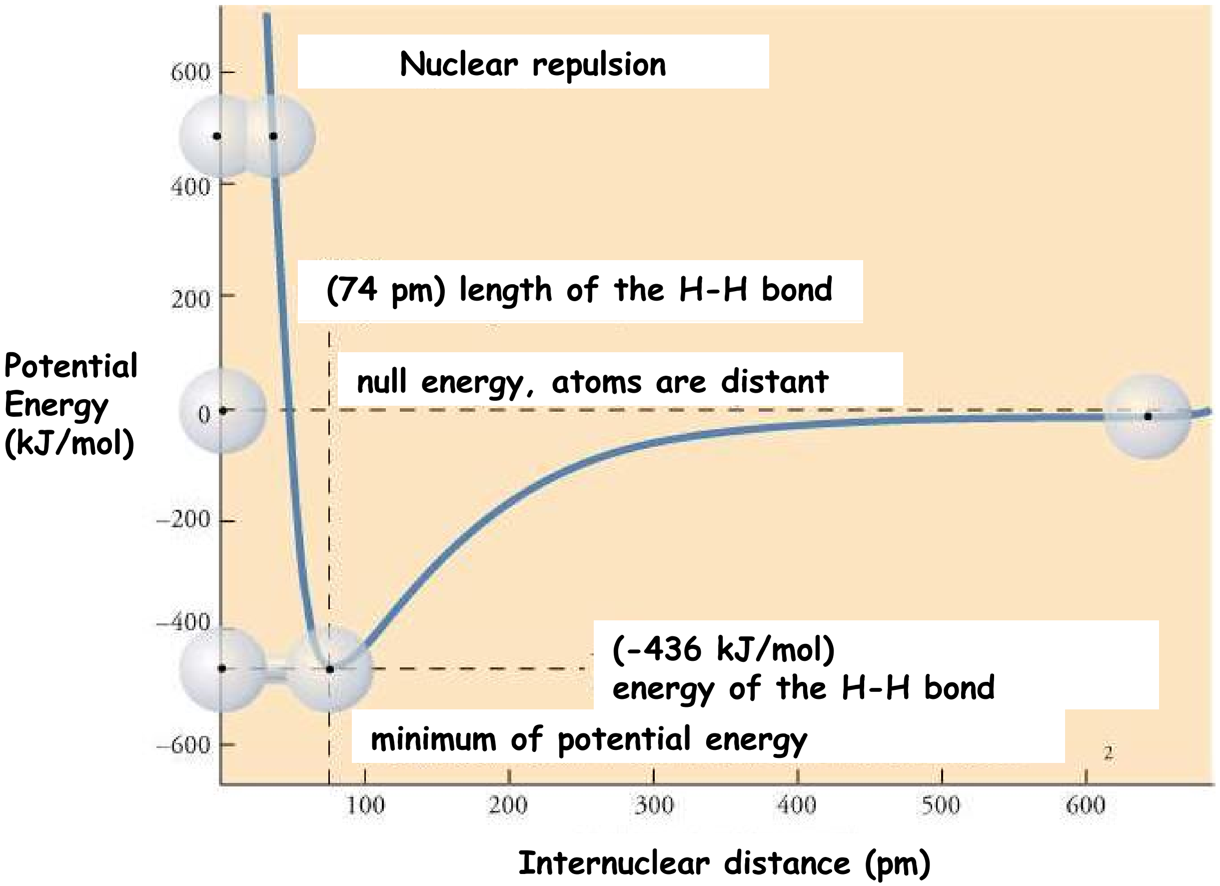
The second step must take into account both the Coulomb attraction and the energy of the reticulum (experimental data).

$$E = \frac{q_1 q_2}{4\pi\varepsilon_0 r} = \frac{k\, q_1 q_2}{r} \quad k = 8{,}99 \times 10^9 \ \mathrm{J \cdot m/C^2}$$

Energy (ΔG^o)= -5/-10 Kcal/mol
Bond distance: 2.7 -3 Å

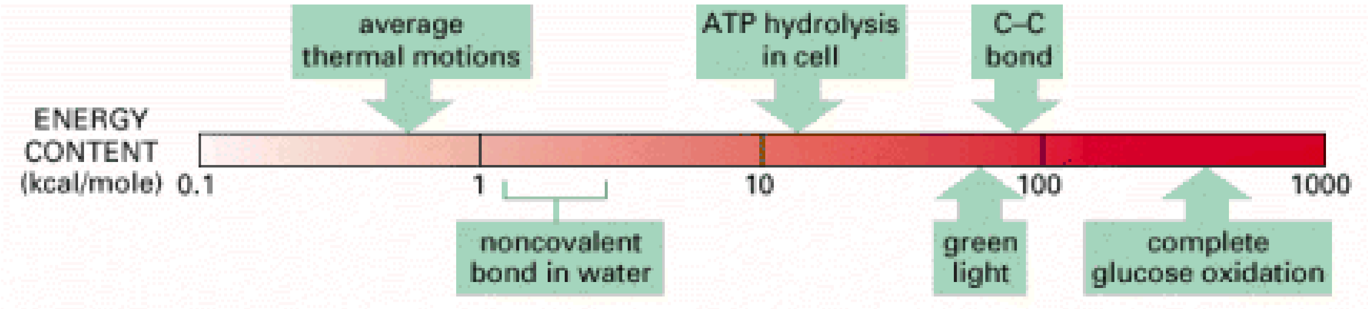
Covalent bonds: an atom often behaves as if it has a fixed radius

Electrons are shared betweeen atoms to complete outer shells, rather than being transferred between them.



Energy (ΔG^{o})= -40/-110 Kcal/mol

Covalent bonds (2)

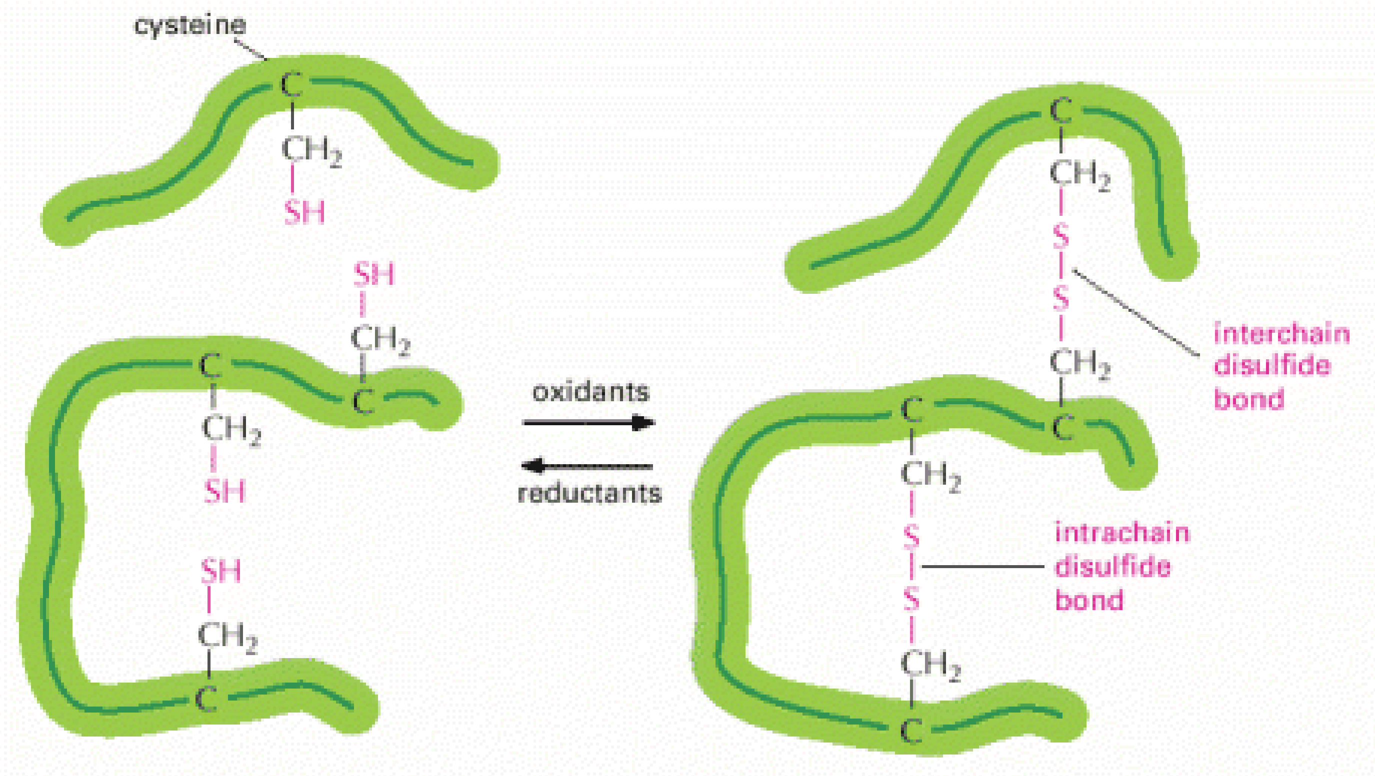


To get an idea of the bond strengths, we compared them with the average energies of the impacts that molecules are constantly undergoing from collisions with other molecules in their environment, as well as with other sources of biological energy such as light.

Typical covalent bonds are stronger than the thermal energies by a factor of 100, so they are normally broken only during specific chemical reactions with other atoms and molecules. This process is controlled by specific proteins, called enzymes.

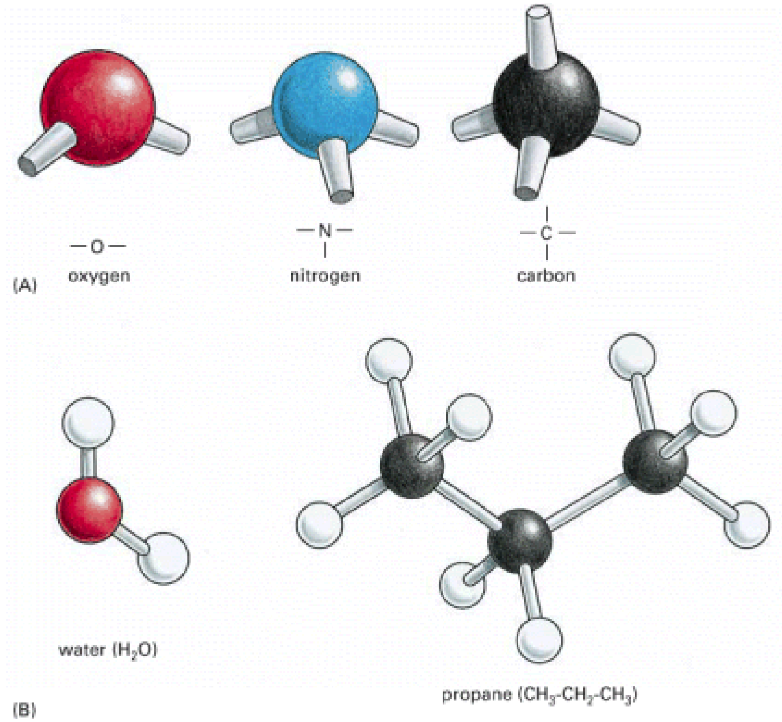
Non covalent bonds are weaker because they are important when molecules have to associate and dissociate readily to carry out their functions.

Covalent bonds: disulphide bond



Two parts of the same polypeptide chain or two different polypeptide chains can be joined together. Since the energy required to break one covalent bond is much larger than the energy required to break even a whole set of noncovalent bonds a disulfide bond can have a major stabilizing effect on a protein. Bond distance: 2.07 Å;
Energy ~ -40 Kcal/mol

There are different types of covalent bonds



When one atom forms covalent bonds with several others, these multiple bonds have definite orientations in space relative to one another, reflecting the orientations of the orbits of the shared electrons.
The 4 covalent bonds that can form around a carbon atom, for example, are arranged as if pointing to four corners of a regular tetrahedron.

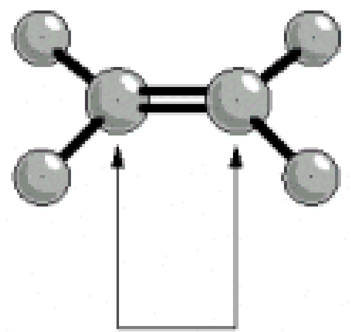
There are different types of covalent bonds

Carbon has a unique role in the cell because of its ability to form strong covalent bonds with other carbon atoms (the energy of the C-C bond is about 348 kJ/mol, with a distance of 154 pm). Molecules in a cell are based on carbon.

Most covalent bonds involve the sharing of two electrons, one donated by each participating atom: single bonds

Four electrons can be shared, for example, two coming from each participating atom: double bonds

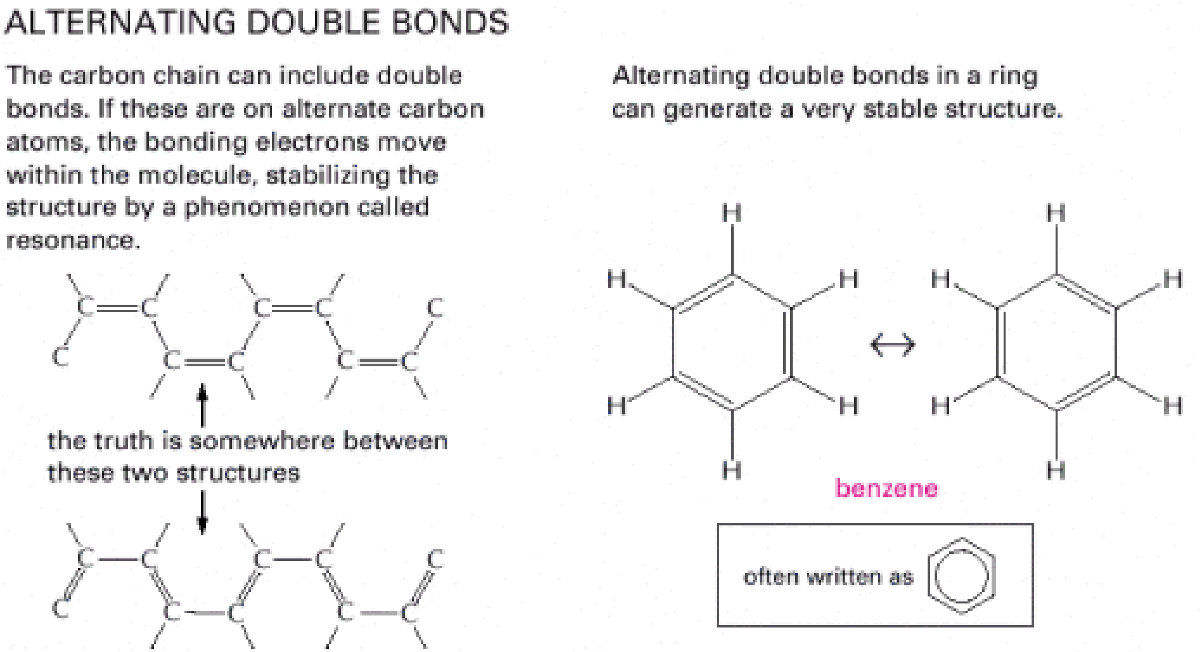
Bond	Distance (pm)	Energy (kJ/mol)
C-C single	154	347
C-C double	135	522
C-C triple	121	961
N-N single	147	159



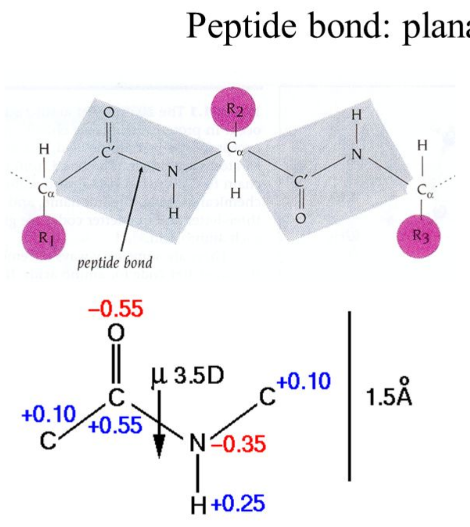
Atoms joined by two or more covalent bonds cannot rotate freely around the bond axis. This restriction is a major influence on the three-dimensional shape of many macromolecules.

There are different types of covalent bonds

Some molecules share electrons between three or more atoms, producing bonds that have a hybrid character intermediate between single and double bonds. The highly stable benzene molecule, for example, comprises a ring of 6 carbon atoms in which the bonding electrons are evenly distributed.



Peptide bond



The partially double character of the peptide bond results in

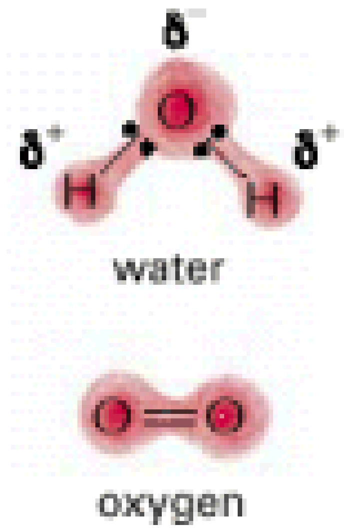
•planarity of peptide groups

•their relatively large dipole moment

8–16 kilojoule/mol (2–4 kcal/mol) of free energy

Polar covalent bonds

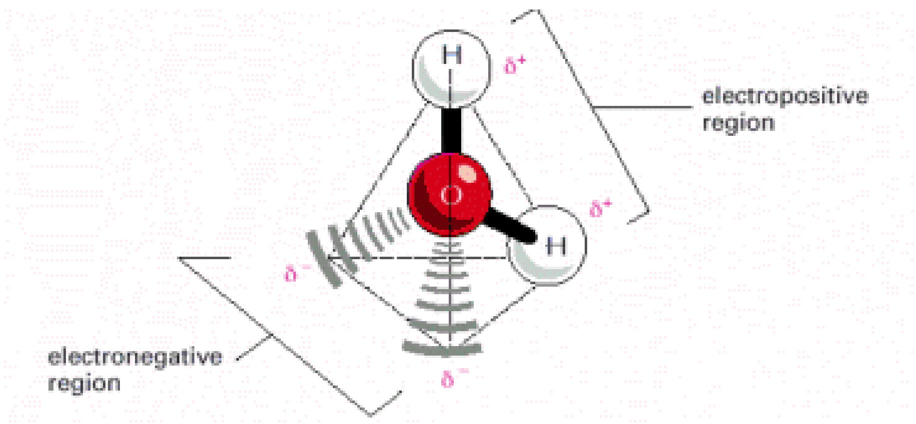
When the atoms joined by a single covalent bond belong to different elements, the two atoms usually attract the shared electrons to different degrees. Compared to a C atom, for example, O and N atoms attract electrons relatively strongly, whereas an H atom attracts electrons more weakly. Covalent bonds in which electrons are shared inequally in this way are known as polar covalent bonds (-O-H, -N-H but no –C-H).



Polar covalent bonds create permanent dipoles that allow molecules to interact through electrical forces.

Water is the most abundant substance in cells

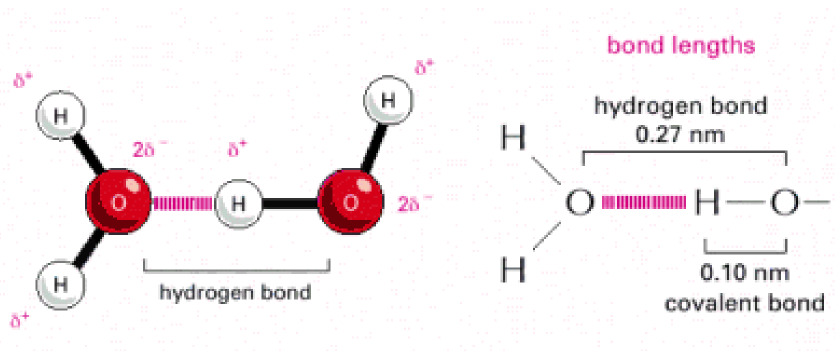
Water accounts for about 70% of a cell's weight and most intracellular interactions occur in an aqueous environment.
In each water molecule the two H atoms are linked to the O atom by covalent bonds. The two bonds are highly polar because the O is strongly attractive for electrons, while the H is only weak attractive.



When a positively charged region of one water molecule (one of its H atoms) comes close to a negatively charged region (the O) of a second water molecule, the electrical attraction between them can result in a weak bond called hydrogen bond.

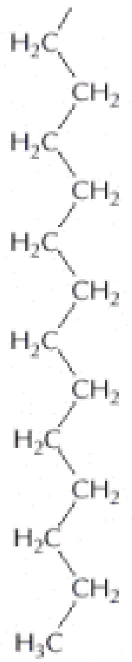
Energy (ΔG^o)= -3/-5 Kcal/mol

Hydrogen bond



These bonds are much weaker than covalent bonds and are easily broken by the random thermal motions.

The combined effect of many weak bonds is not trivial. Each water molecule can form hydrogen bonds through its two H atoms with two other water molecules, producing a network in which hydrogen bonds are being continually broken and formed.

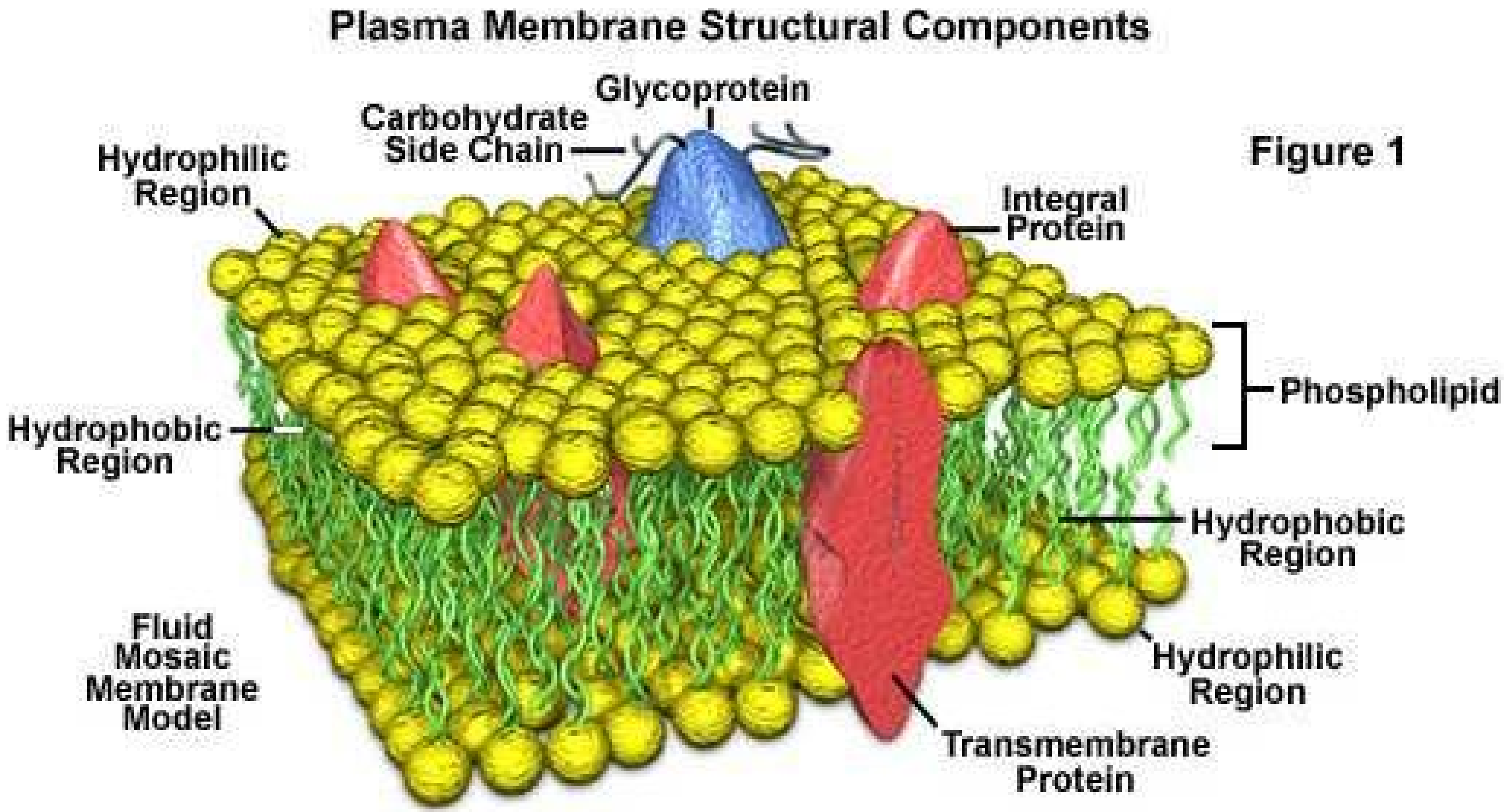


part of the hydrocarbon "tail" of a fatty acid molecule

Hydrocarbons, stable compounds of largely non polar bonds of carbon and hydrogen. They are non polar, do not form hydrogen bonds and are generally insoluble in water.

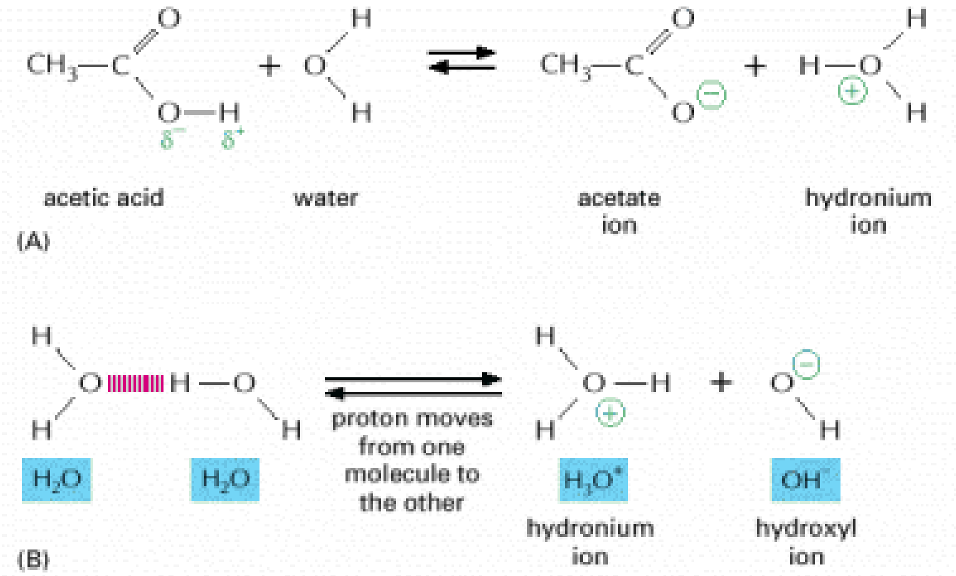
90% of the C=O and N-H groups of the backbone forms hydrogen bonds.
N-H groups form single bonds while 35% of the C=O groups can be involved in two or three hydrogen bonds.

Cell membrane



Hydrocarbons are hydrophobic molecules. This property is exploited in cells, whose membranes are constructed from molecules that have long hydrocarbon chains.

Some polar molecules form acids and bases in water



A molecule possessing a highly polar covalent bond between a hydrogen and a second atom dissolves in water. Substances that release protons to form H_3O^+ are termed acids.

$pH = -\log_{10}[H^+]$
For pure water $[H^+] = 10^{-7}$ mol/l

The opposite of an acid is a base. The defining property of a base is that it raises the concentration of hydroxyl (OH^-) ions, which are formed by removal of a proton from a water molecule.

Henderson-Hasselbalch equation

Consider the ionization of a weak acid HA which has some pK_a. It is often convenient to be able to relate the pH of a solution of a weak acid to the pK_a of the acid and the extent of ionization. The reaction would be

HA (reversible arrows) $H^+ + A^-$

The acid dissociation constant (K_a) for this reaction would be given by the equation

$$K_a = \frac{[H^+][A^-]}{[HA]}$$

This equation can be rearranged to isolate the hydrogen ion concentration on the left, because, remember, we want an equation relating the pH of the solution to the pK_a and the extent of ionization of the weak acid. The rearranged form of the equation is

$$\frac{1}{[H^+]} = \frac{1}{[K_a]}\frac{[A^-]}{[HA]}$$

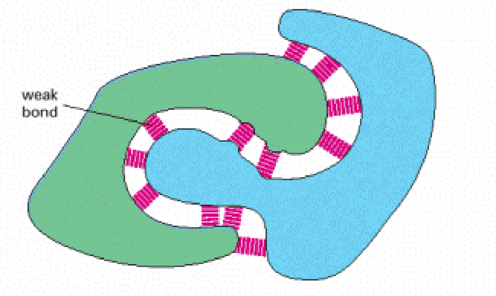
By definition, $\log 1/[H^+] = pH$, and $\log 1/K_a = pK_a$, so that by taking the log of the equation above, we get the equation

$$pH = pK_a + \log\frac{[A^-]}{[HA]}$$

This is the well-known Henderson-Hasselbalch equation that is often used to perform the calculations required in preparation of buffers for use in the laboratory, or other applications. Notice several interesting facts about this equation.

First, if the pH = pK_a, the log of the ratio of dissociate acid and associated acid will be zero, so the concentrations of the two species will be the same. In other words, when the pH equals the pK_a, the acid will be half dissociated.

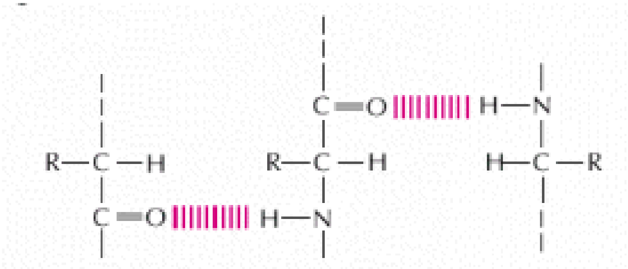
Four types of noncovalent interactions help bring molecules together in cells



The binding of different molecules to each other is mediated by a group on noncovalent interactions that are individually quite weak, but whose bond energies can sum to create an effective force.

-Ionic bonds, purely electrostatic attractions

- Hydrogen bonds, highly directional



- van der Waals attractions, the electron cloud around any nonpolar atom will fluctuate, producing a transient dipole. Such dipoles induce an oppositely polarization in a nearby atom. This interaction generates an attraction between atoms that is very weak. They are not weakened by water.

Energy (ΔG^{o})= -0.5 Kcal/mol

Four types of noncovalent interactions help bring molecules together in cells

BOND TYPE	LENGTH (nm)	STRENGTH (kcal/mole) IN VACUUM	IN WATER
Covalent	0.15	90	90
Noncovalent: ionic	0.25	80	3
hydrogen	0.30	4	1
van der Waals attraction (per atom)	0.35	0.1	0.1

Hydrophobic effect: this force is caused by a pushing of nonpolar surfaces out of the hydrogen-bonded water network, where they would physically interfere with the highly favorable interactions between water molecules. Energy (ΔG^o)= -0.7/-1 Kcal/mol