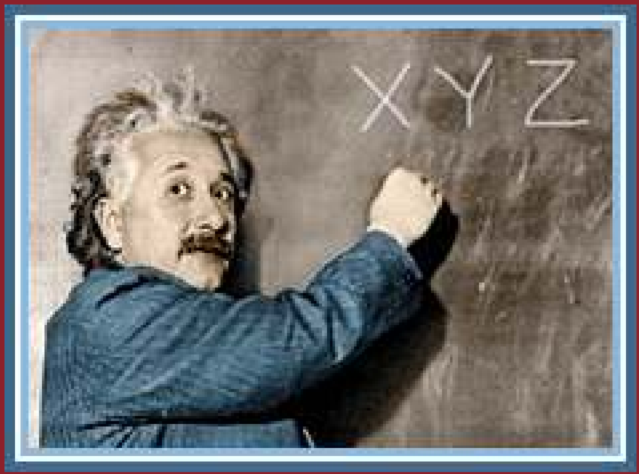
# 2

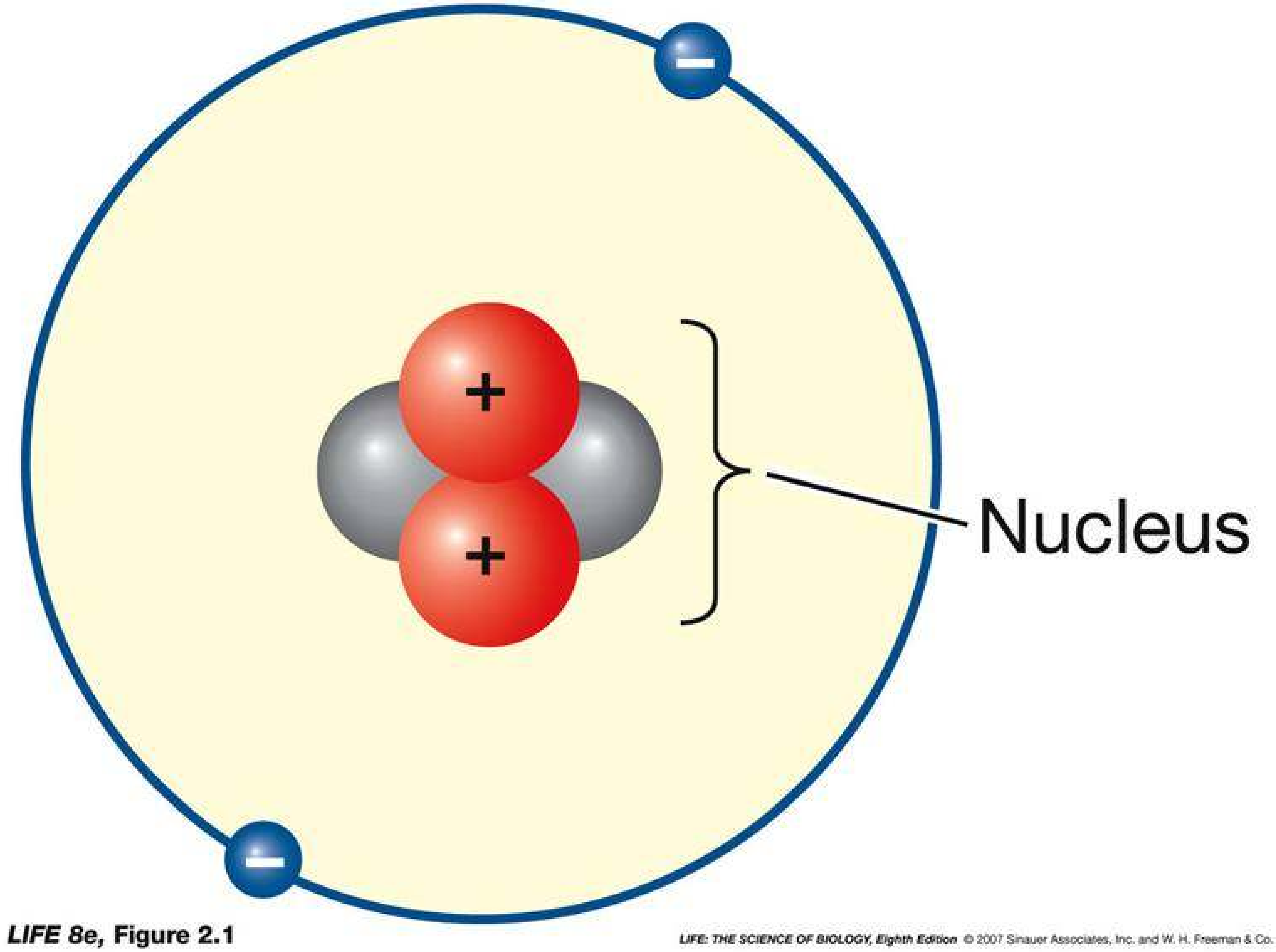
# *The Chemistry of Life*

*aka 1 year of Chemistry crammed into one lesson!*




- 2.1 What Are the Chemical Elements That Make Up Living Organisms?
- 2.2 How Do Atoms Bond to Form Molecules?
- 2.3 How Do Atoms Change Partners in Chemical Reactions?
- 2.4 What Properties of Water Make It So Important in Biology?

## Figure 2.1 The Helium Atom




All matter is composed of **atoms**

## 2.1 What Are the Chemical Elements That Make Up Living Organisms?

Atoms have volume and mass.

Mass of one proton or one neutron = **atomic mass unit** (amu) or 1 *dalton*, or $1.7 \times 10^{-24}$ grams.

Mass of one electron = $9 \times 10^{-28}$

usually ignored

## 2.1 What Are the Chemical Elements That Make Up Living Organisms?

**Protons**: positive charge +1

**Electrons**: negative charge –1

**Neutrons**: zero charge

**Atoms**: # protons = # electrons—electrically neutral

# 2.1 What Are the Chemical Elements That Make Up Living Organisms?

**Element**: pure substance containing only one kind of atom

Elements are arranged in the **periodic table**.

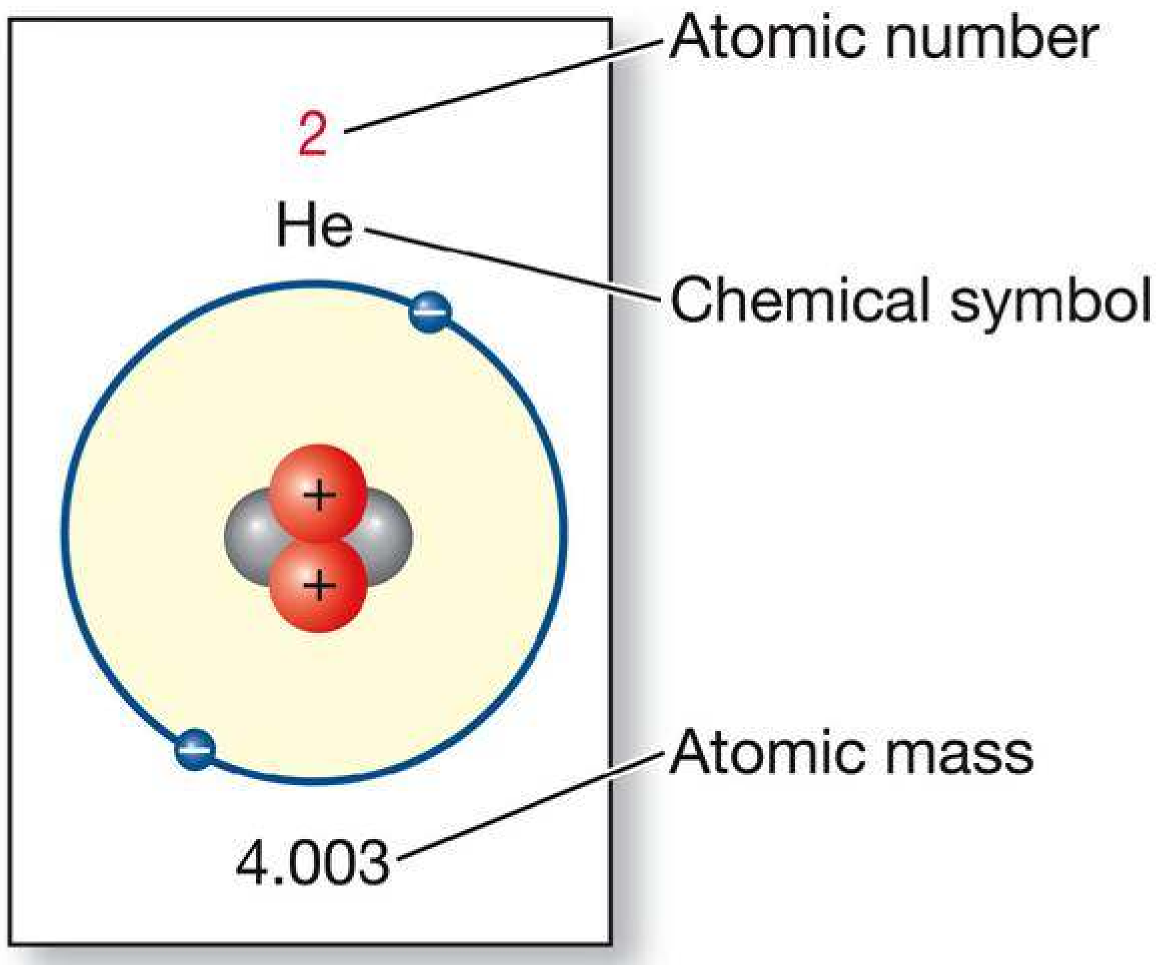
# Figure 2.2 The Periodic Table (Part 1)

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 H 1.0079 | | | | | | | | | | | | | | | | | 2 He 4.003 |
| 3 Li 6.941 | 4 Be 9.012 | | | | | | | | | | | 5 B 10.81 | 6 C 12.011 | 7 N 14.007 | 8 O 15.999 | 9 F 18.998 | 10 Ne 20.179 |
| 11 Na 22.990 | 12 Mg 24.305 | | | | | | | | | | | 13 Al 26.982 | 14 Si 28.086 | 15 P 30.974 | 16 S 32.06 | 17 Cl 35.453 | 18 Ar 39.948 |
| 19 K 39.098 | 20 Ca 40.08 | 21 Sc 44.956 | 22 Ti 47.88 | 23 V 50.942 | 24 Cr 51.996 | 25 Mn 54.938 | 26 Fe 55.847 | 27 Co 58.933 | 28 Ni 58.69 | 29 Cu 63.546 | 30 Zn 65.38 | 31 Ga 69.72 | 32 Ge 72.59 | 33 As 74.922 | 34 Se 78.96 | 35 Br 79.909 | 36 Kr 83.80 |
| 37 Rb 85.4778 | 38 Sr 87.62 | 39 Y 88.906 | 40 Zr 91.22 | 41 Nb 92.906 | 42 Mo 95.94 | 43 Tc (99) | 44 Ru 101.07 | 45 Rh 102.906 | 46 Pd 106.4 | 47 Ag 107.870 | 48 Cd 112.41 | 49 In 114.82 | 50 Sn 118.69 | 51 Sb 121.75 | 52 Te 127.60 | 53 I 126.904 | 54 Xe 131.30 |
| 55 Cs 132.905 | 56 Ba 137.34 | 71 Lu 174.97 | 72 Hf 178.49 | 73 Ta 180.948 | 74 W 183.85 | 75 Re 186.207 | 76 Os 190.2 | 77 Ir 192.2 | 78 Pt 195.08 | 79 Au 196.967 | 80 Hg 200.59 | 81 Tl 204.37 | 82 Pb 207.19 | 83 Bi 208.980 | 84 Po (209) | 85 At (210) | 86 Rn (222) |
| 87 Fr (223) | 88 Ra 226.025 | 103 Lr (260) | 104 Rf (261) | 105 Db (262) | 106 Sg (266) | 107 Bh (264) | 108 Hs (269) | 109 Mt (268) | 110 (269) | 111 (272) | 112 (277) | 113 | 114 (285) | 115 (289) | 116 | 117 | 118 (293) |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lanthanide series | 57 La 138.906 | 58 Ce 140.12 | 59 Pr 140.9077 | 60 Nd 144.24 | 61 Pm (145) | 62 Sm 150.36 | 63 Eu 151.96 | 64 Gd 157.25 | 65 Tb 158.924 | 66 Dy 162.50 | 67 Ho 164.930 | 68 Er 167.26 | 69 Tm 168.934 | 70 Yb 173.04 |
| Actinide series | 89 Ac 227.028 | 90 Th 232.038 | 91 Pa 231.0359 | 92 U 238.02 | 93 Np 237.0482 | 94 Pu (244) | 95 Am (243) | 96 Cm (247) | 97 Bk (247) | 98 Cf (251) | 99 Es (252) | 100 Fm (257) | 101 Md (258) | 102 No (259) |

***LIFE 8e*, Figure 2.2 (Part 1)**

# Figure 2.2 The Periodic Table (Part 2)




LIFE 8e, Figure 2.2 (Part 2)



The number of protons identifies an element.
Number of protons = **atomic number.**

All elements except hydrogen have one or more neutrons.

**Mass number** = number of protons + number of neutrons.

Mass number ≈ mass of atom in daltons.

**Isotopes**: forms of an element with different numbers of neutrons, thus different mass numbers

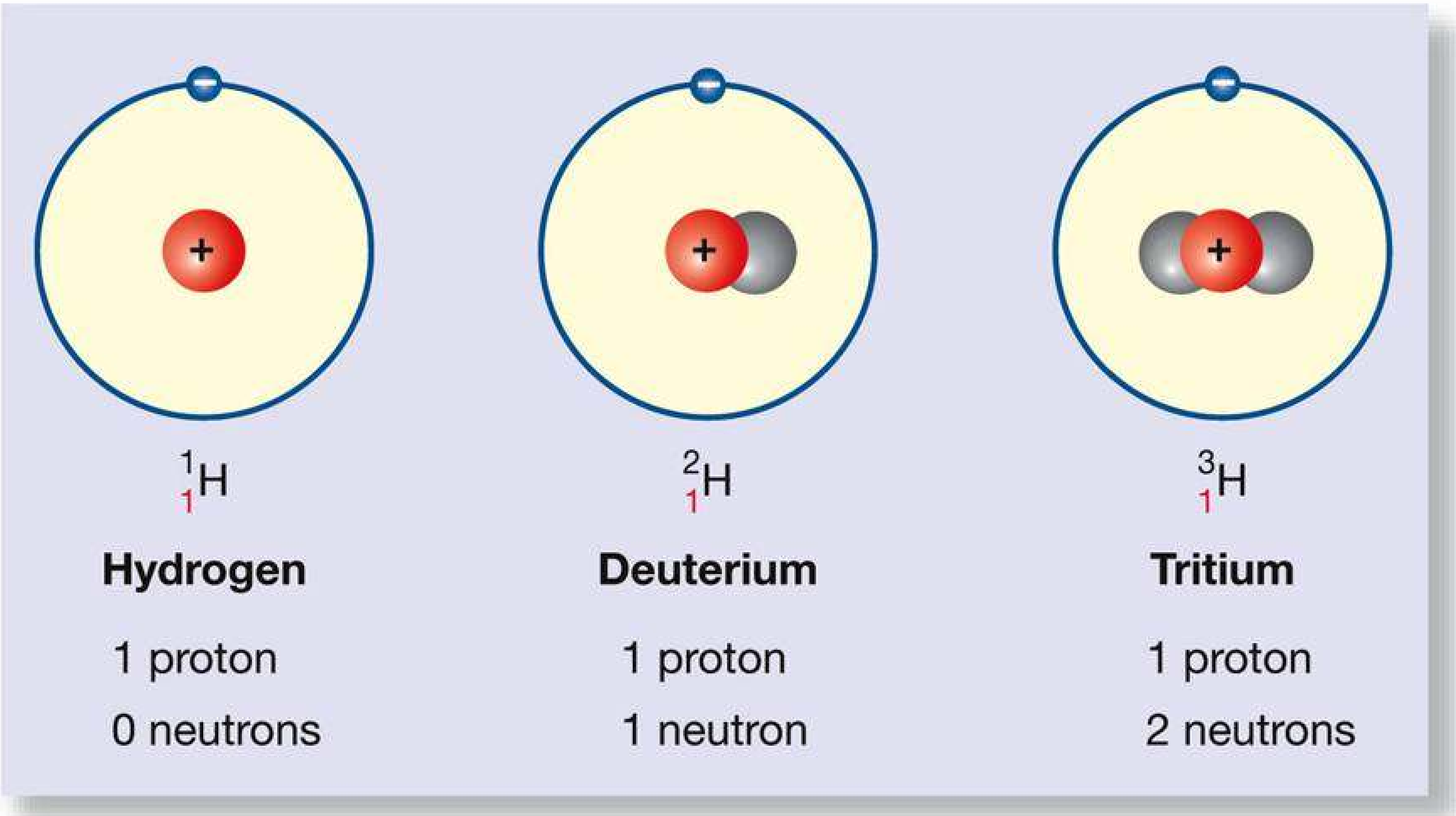
Example:

$^{12}C$ has 6 neutrons

$^{13}C$ has 7 neutrons

$^{14}C$ has 8 neutrons

# Figure 2.3 Isotopes Have Different Numbers of Neutrons




*LIFE 8e*, Figure 2.3

## 2.1 What Are the Chemical Elements That Make Up Living Organisms?

**Atomic weight**: average of mass numbers of isotopes in their normally occurring proportions

Atomic weight of carbon = 12.011

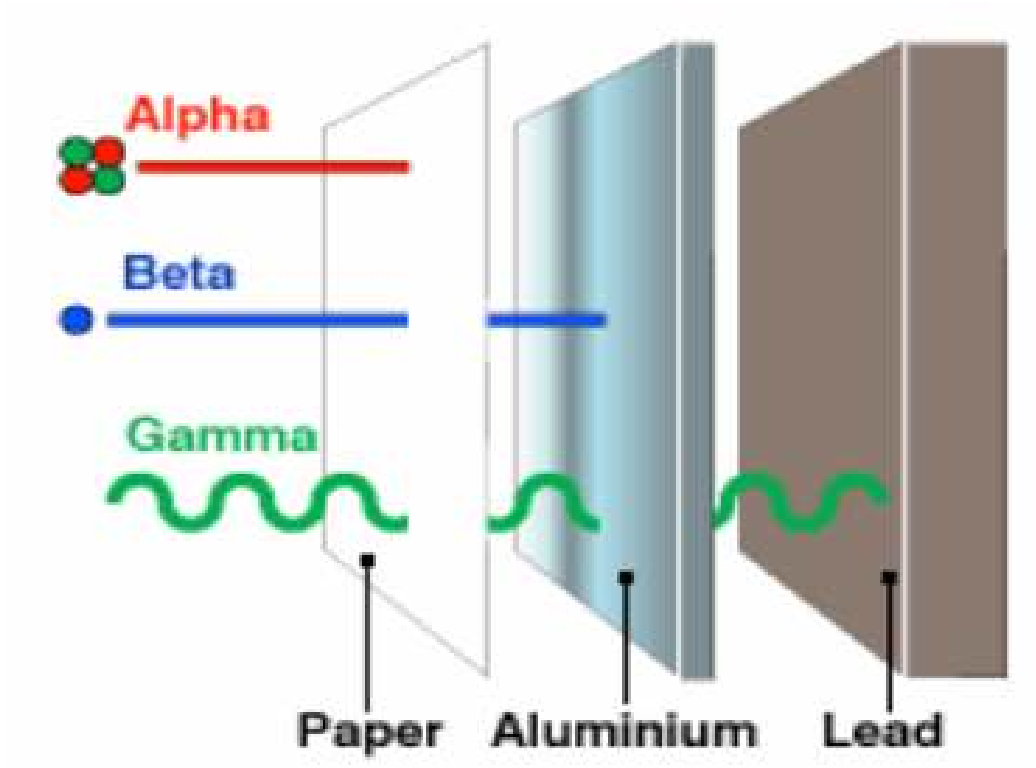
Atomic weight of hydrogen = 1.0079

# 2.1 What Are the Chemical Elements That Make Up Living Organisms?

**Radioisotopes** are unstable, they give off energy in the form of alpha, beta, and gamma radiation from the nucleus.

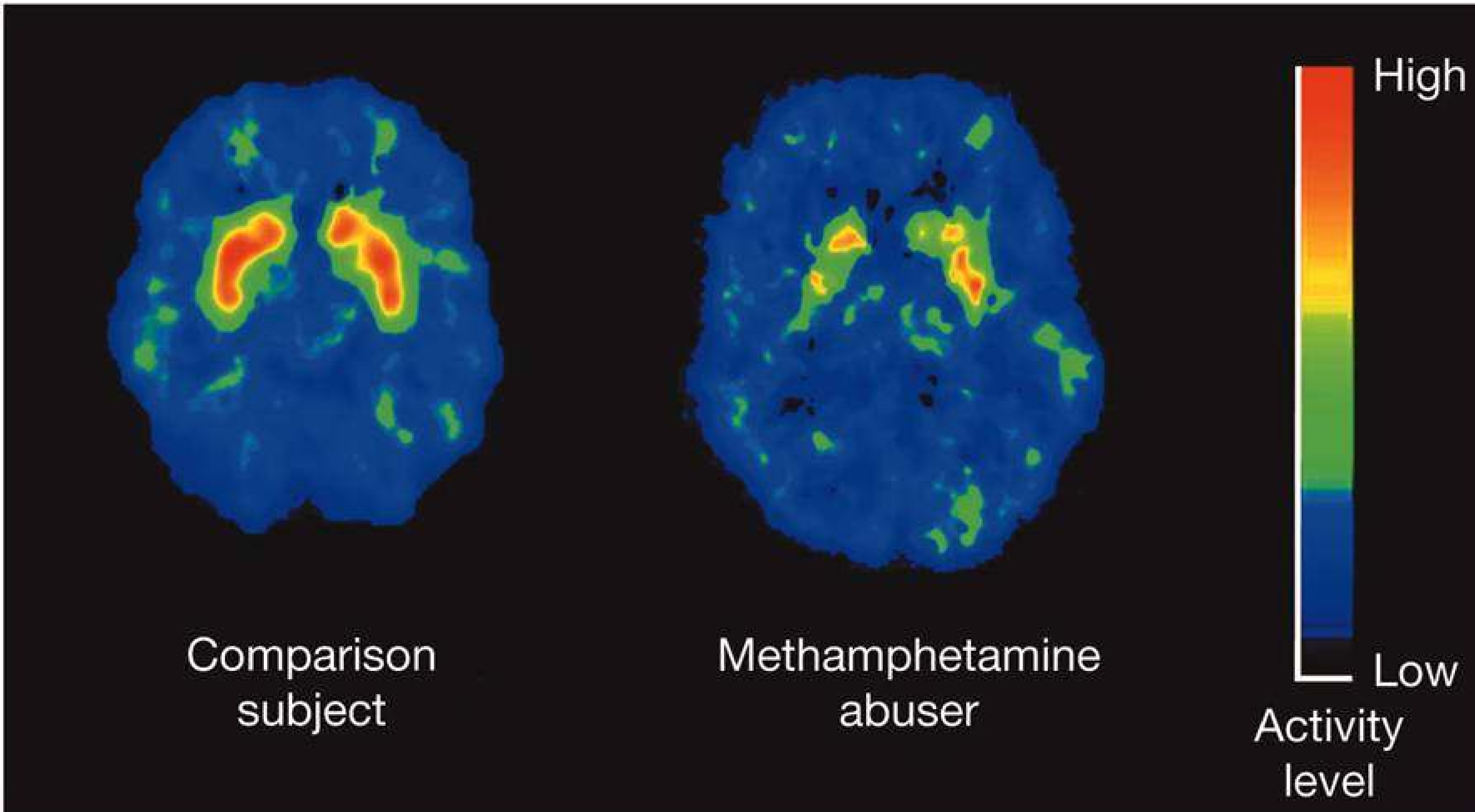
- **Alpha** - An atom spits out two protons and two neutrons from its nucleus. Stopped by a piece of paper.
- **Beta** - In beta decay a neutron sends its electron packing, literally ejecting it from the nucleus at high speed. The result? That neutron turns into a proton! Stopped by a piece of wood.
- **Gamma** - Gamma rays is electromagnetic radiation similar to light. Gamma decay does not change the mass or charge of the atom from which it originates. Gamma is often emitted along with alpha or beta particle ejection. Stopped by lead.

## 2.1 Alpha, Beta, and Gamma Particles



## Figure 2.4 Tagging the Brain

Energy from radioactive decay can interact with surrounding material. Radioisotopes can be incorporated into molecules and act as a “tag” or label.




LIFE 8e, Figure 2.4

# 2.1 The good and bad of radiation.

Radiation can damage cells and tissues.

It is sometimes used to treat cancer.

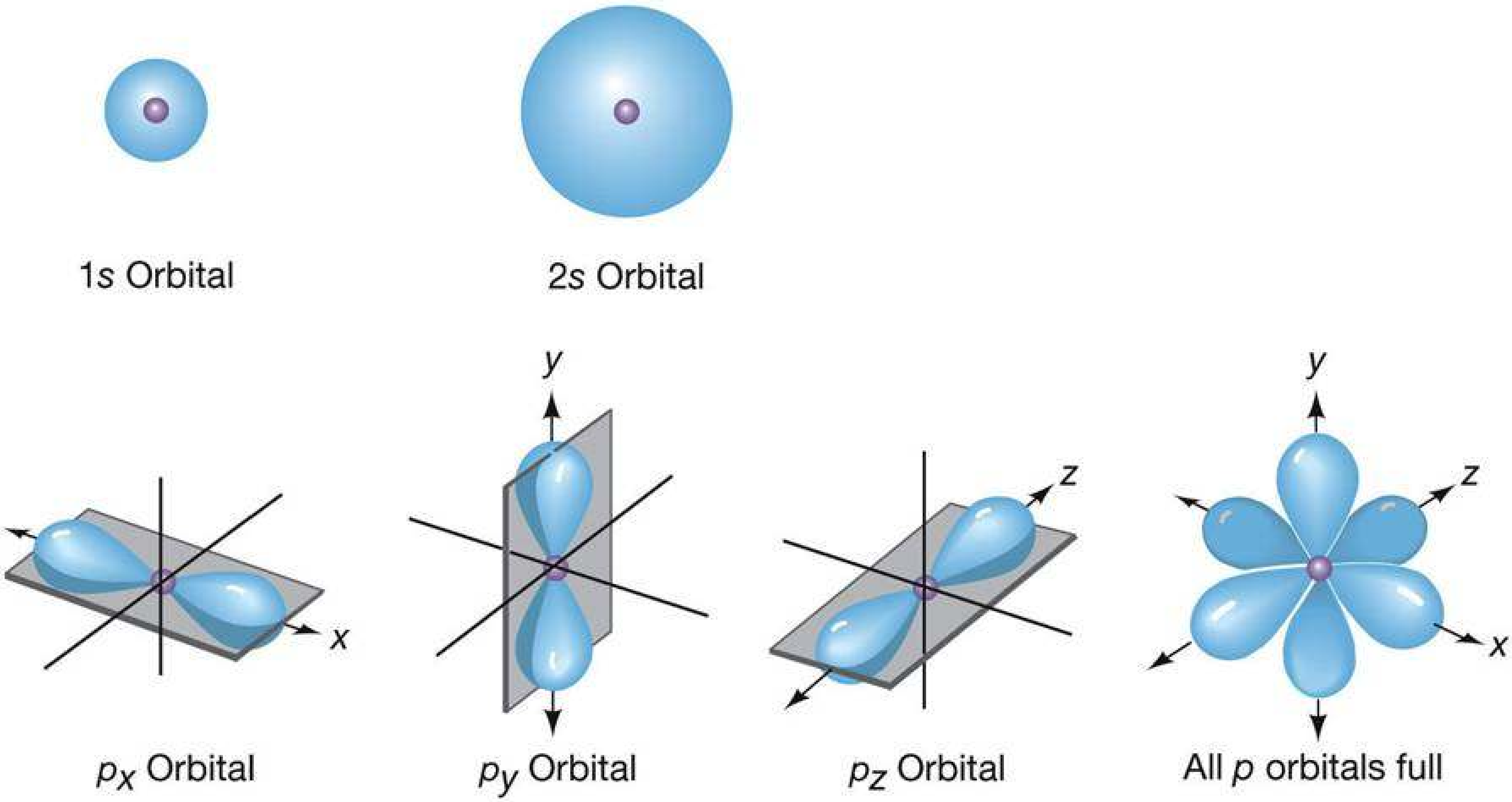
# 2.1 What Are the Chemical Elements That Make Up Living Organisms?

- The **number of electrons** determines how atoms will interact.
- Chemical reactions involve changes in the distribution of **electrons** between atoms.
- In other words, it is the electrons in the **outer shell** of an atom that interact with the electrons in the outer shell of another atom.

Locations of electrons in an atom are described by **orbitals**.

- Orbital: region where electron is found at least 90 percent of the time.
- Orbitals have characteristic shapes and orientations, and can be occupied by two electrons.
- Orbitals are filled in a specific sequence.

# Figure 2.5 Electron Orbitals



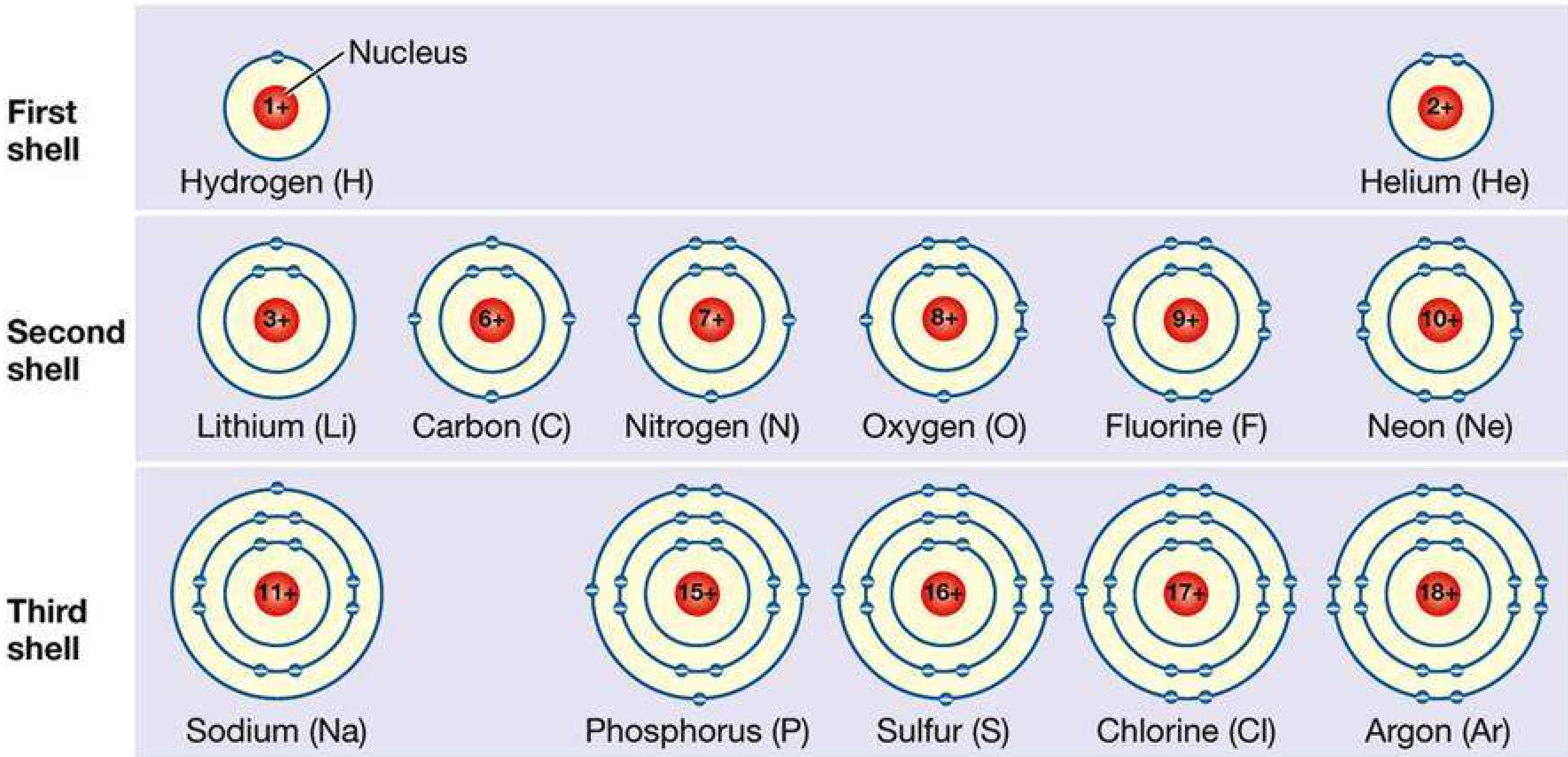

LIFE 8e, Figure 2.5

## 2.1 What Are the Chemical Elements That Make Up Living Organisms?

Orbitals occur in series called **electron shells** or *energy levels*.

- First shell: one orbital—*s* orbital
- Second shell: one *s* and three *p* orbitals (holds eight electrons)
- Additional shells: four orbitals (eight electrons)
- http://bcs.whfreeman.com/thelifewire8e/content/cat_010/02050-01.htm

# Figure 2.6 Electron Shells Determine the Reactivity of Atoms




***LIFE* 8e, Figure 2.6**

# 2.1 What Are the Chemical Elements That Make Up Living Organisms?

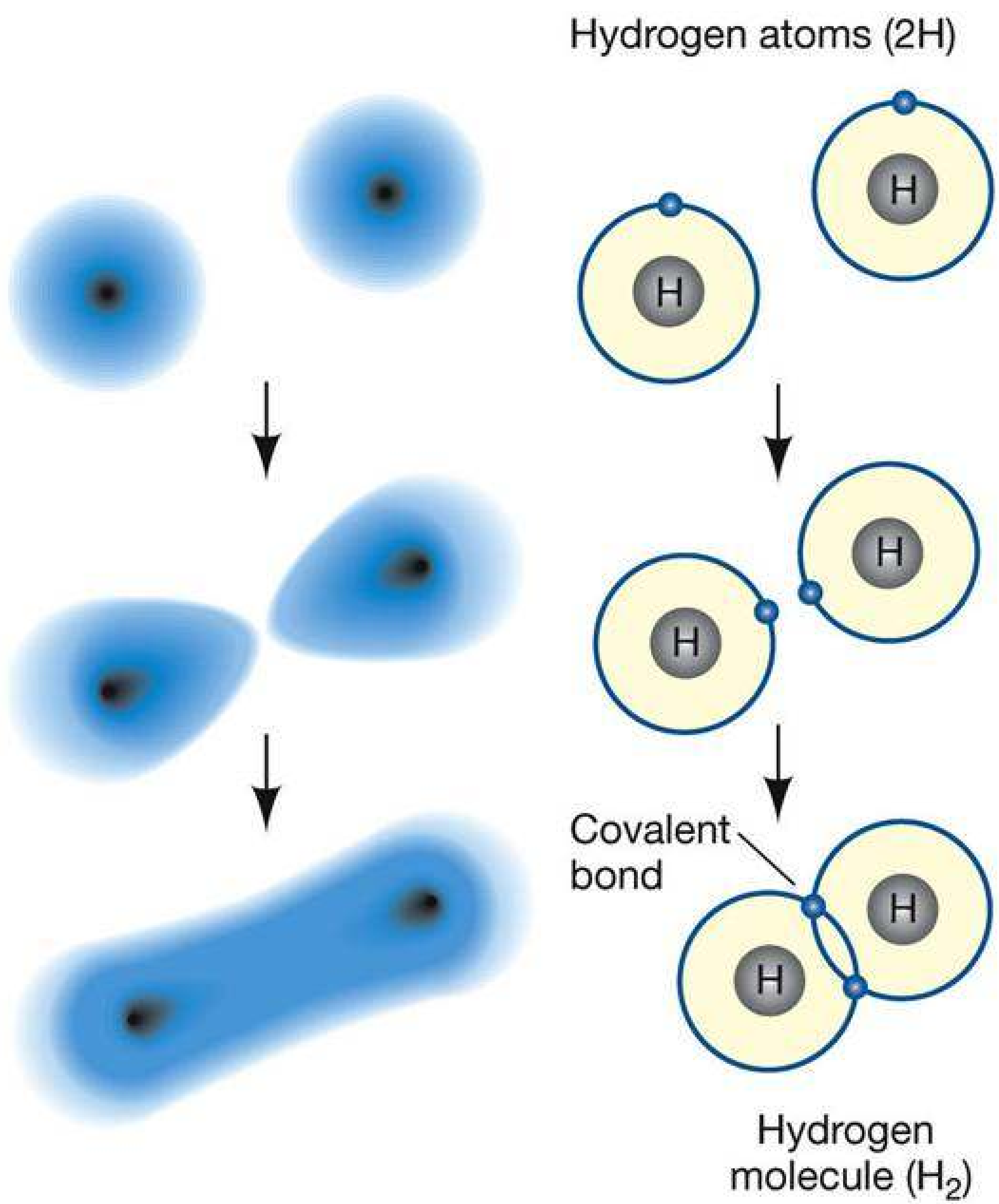
- *Reactive* atoms have unpaired electrons in their outermost shell.
- Atoms can share electrons, or loose or gain electrons, resulting in atoms *bonded* together to form **molecules**.
- The **octet rule** is a chemical rule of thumb that states that atoms of low (<20) atomic number tend to combine in such a way that they each have eight electrons in their valence shells, giving them the same electronic configuration as a noble gas.

# 2.2 How Do Atoms Bond to Form Molecules?

**Chemical bond**: attractive force that links atoms together to form molecules

**Covalent bonds**: atoms share one or more pairs of electrons, so that the outer shells are filled.

# Figure 2.7 Electrons Are Shared in Covalent Bonds

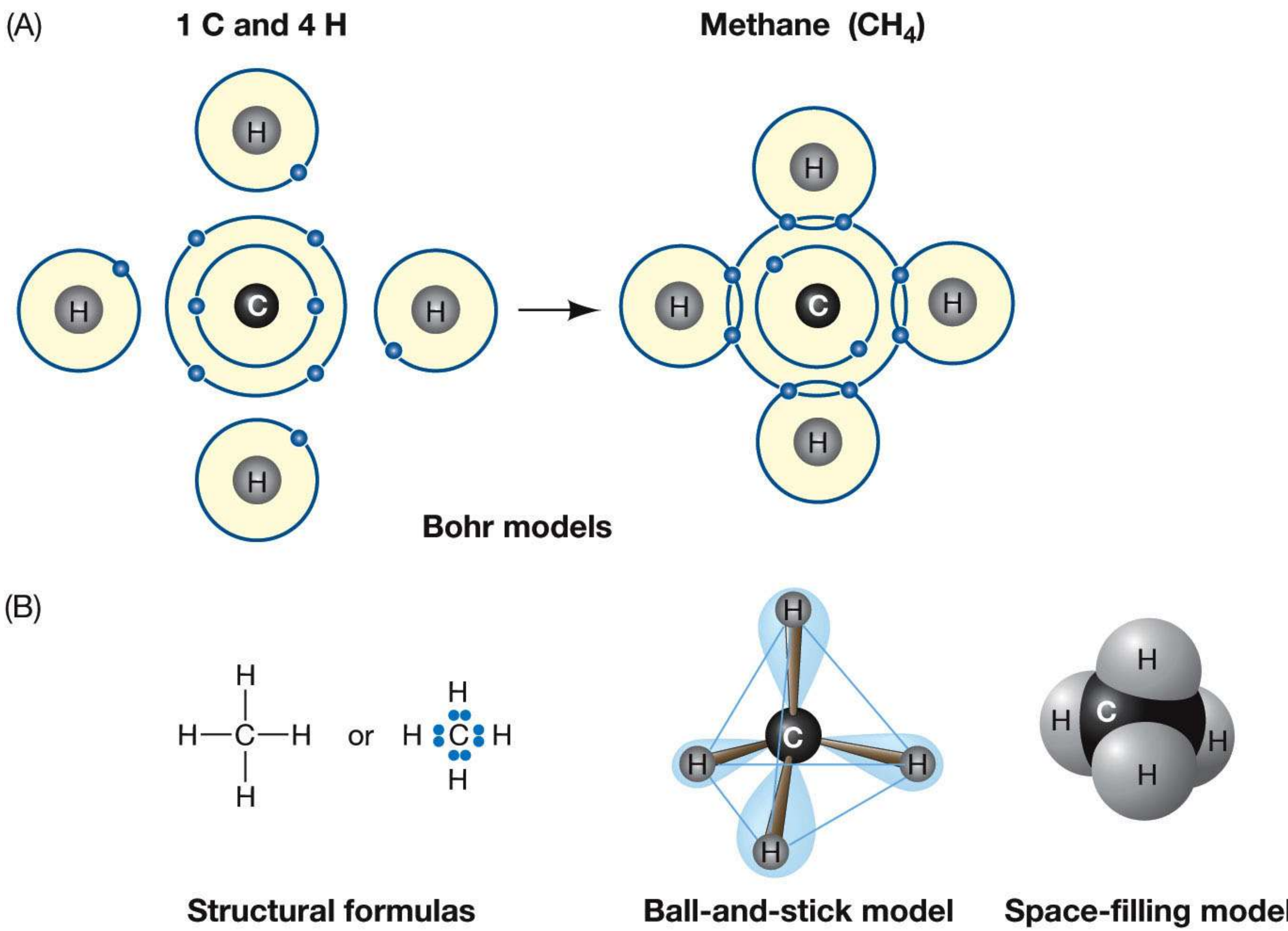



LIFE 8e, Figure 2.7

**Compound**: a molecule made up of two or more elements.

The **molecular weight** of a compound is the sum of the atomic weights of all atoms in the molecule.

## Figure 2.8 Covalent Bonding Can Form Compounds




Carbon can form four covalent bonds.

TABLE 2.2

# Covalent Bonding Capabilities of Some Biologically Important Elements

| ELEMENT | USUAL NUMBER OF COVALENT BONDS |
|---|---|
| Hydrogen (H) | 1 |
| Oxygen (O) | 2 |
| Sulfur (S) | 2 |
| Nitrogen (N) | 3 |
| Carbon (C) | 4 |
| Phosphorus (P) | 5 |

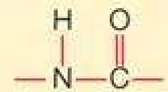
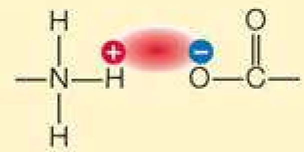
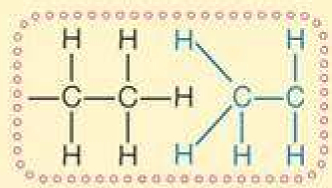
***LIFE* 8e, Table 2.2**

Covalent bonds are very strong—a lot of energy is required to break them.

Biological molecules are put together with covalent bonds and are very stable.

**TABLE 2.1**

## Chemical Bonds and Interactions

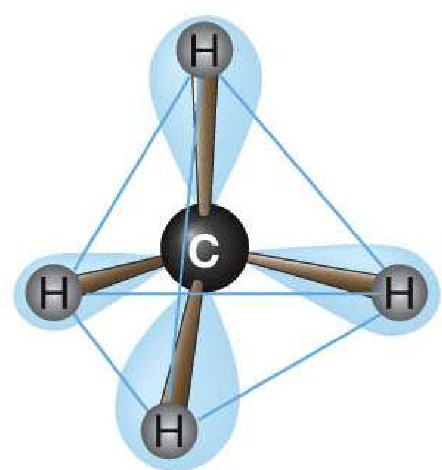
| NAME | BASIS OF INTERACTION | STRUCTURE | BOND ENERGY[a] (KCAL/MOL) |
|---|---|---|---|
| Covalent bond | Sharing of electron pairs |  | 50–110 |
| Ionic bond | Attraction of opposite changes |  | 3–7 |
| Hydrogen bond | Sharing of H atom |  | 3–7 |
| Hydrophobic interaction | Interaction of nonpolar substances in the presence of polar substances (especially water) |  | 1–2 |
| van der Waals interaction | Interaction of electrons of nonpolar substances |  | 1 |

[a]*Bond energy* is the amount of energy needed to separate two bonded or interacting atoms under physiological conditions.

Orientation of bonds:

The length, angle, and direction of bonds between any two elements are always the same.

Example: Methane always forms a tetrahedron.



Covalent bonds can be

- *Single*—sharing one pair of electrons

$$C{-}H$$

- *Double*—sharing two pairs of electrons

$$C{=}C$$

- *Triple*—sharing three pairs of electrons

$$N{\equiv}N$$

## 2.2 How Do Atoms Bond to Form Molecules?

**Electronegativity**: the attractive force that an atomic nucleus exerts on electrons

Electronegativity depends on the number of positive charges (protons) and the distance between the nucleus and electrons.

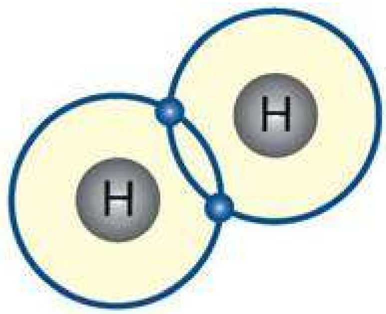
TABLE 2.3

## Some Electronegativities

| ELEMENT | ELECTRONEGATIVITY |
|---|---|
| Oxygen (O) | 3.5 |
| Chlorine (Cl) | 3.1 |
| Nitrogen (N) | 3.0 |
| Carbon (C) | 2.5 |
| Phosphorus (P) | 2.1 |
| Hydrogen (H) | 2.1 |
| Sodium (Na) | 0.9 |
| Potassium (K) | 0.8 |

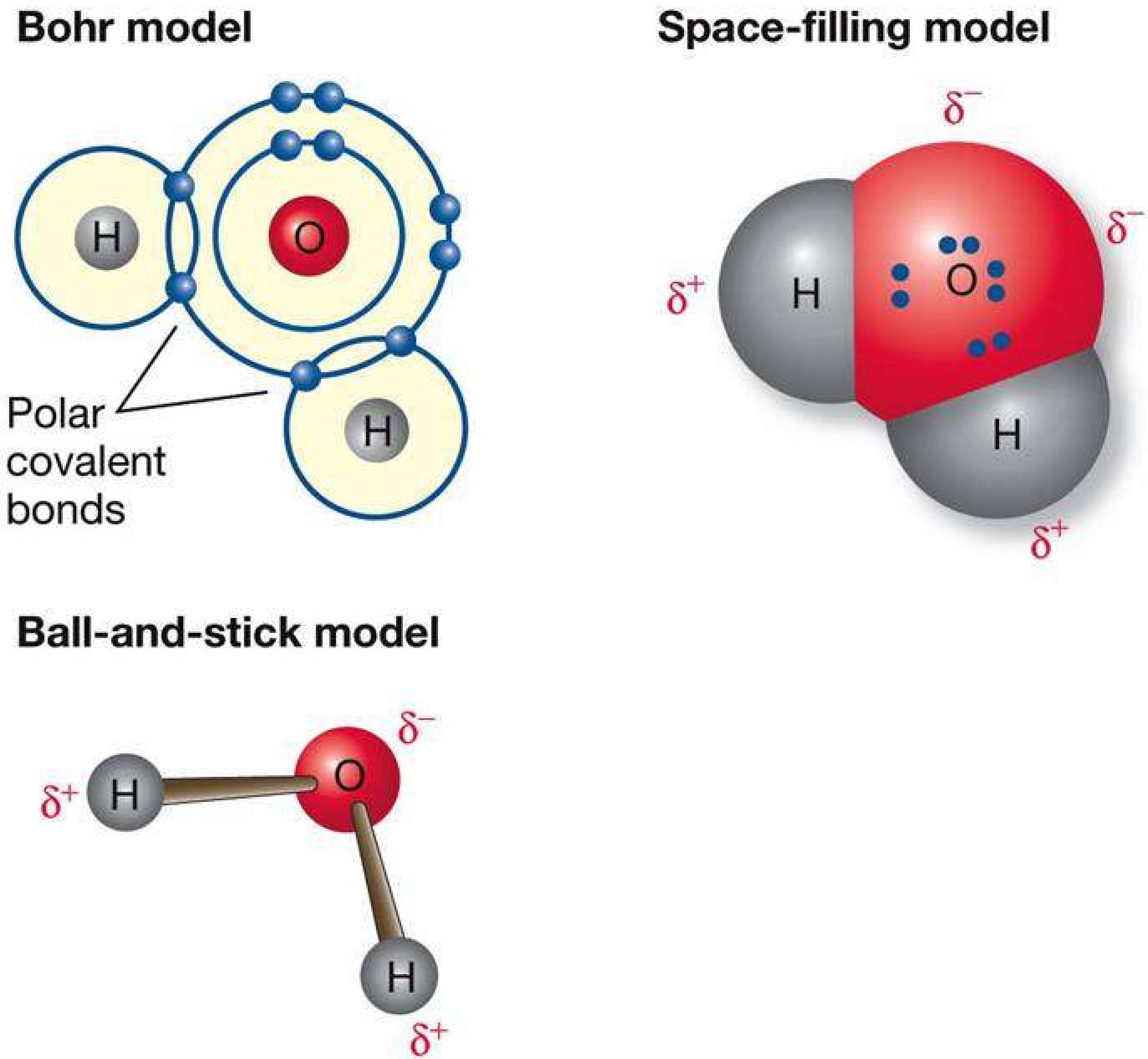
# 2.2 How Do Atoms Bond to Form Molecules?

If two atoms have similar electronegativity, they will share electrons equally—*nonpolar covalent bond.*




If one atom has more electronegativity, the electrons are drawn to that nucleus. Electrons not shared equally—*polar covalent bond.*

# Figure 2.9 Water’s Covalent Bonds are Polar




***LIFE* 8e, Figure 2.9**

**Ions**: electrically charged particles—when atoms loose or gain electrons

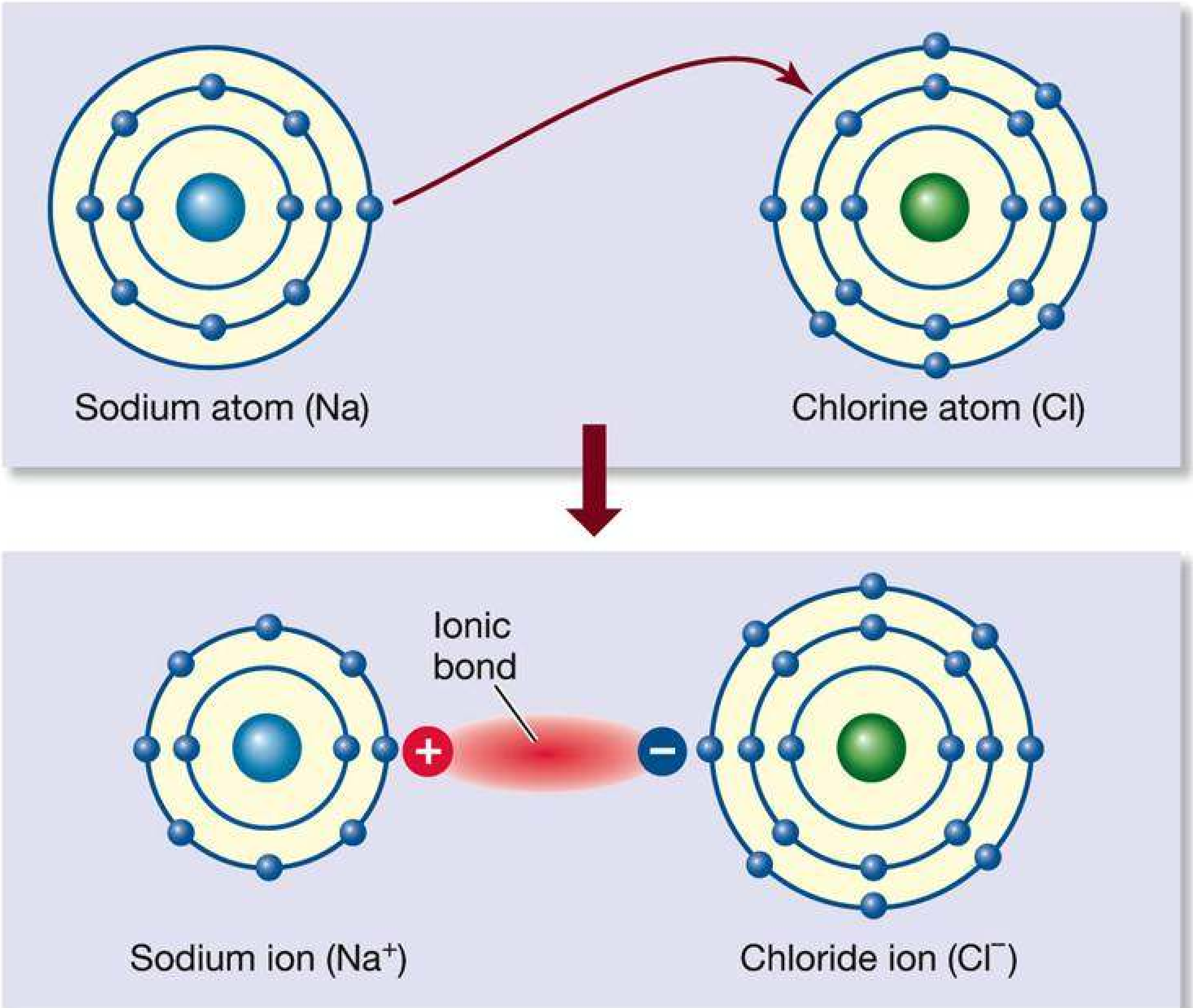
**Cations**—positive

**Anions**—negative

**Ionic bonds** are formed by the electrical attraction of positive and negative ions.

*Salts*—ionically bonded compounds

# Figure 2.10 Formation of Sodium and Chloride Ions



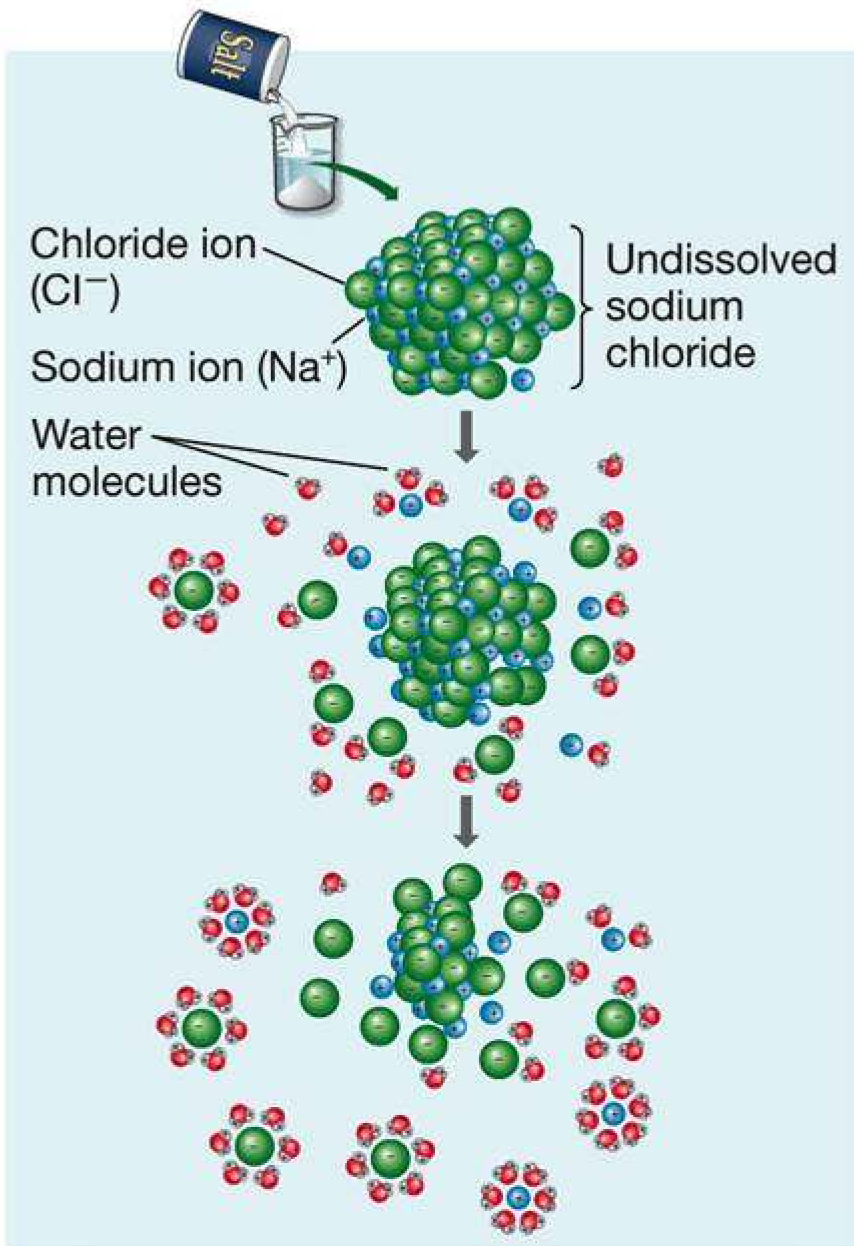

**LIFE 8e, Figure 2.10**

In a solid, ions are close together and the ionic bond is strong.

In water, the ions are far apart and the attraction is much weaker.

Ions interact with polar molecules—salts dissolve in water.

# Figure 2.11 Water Molecules Surround Ions

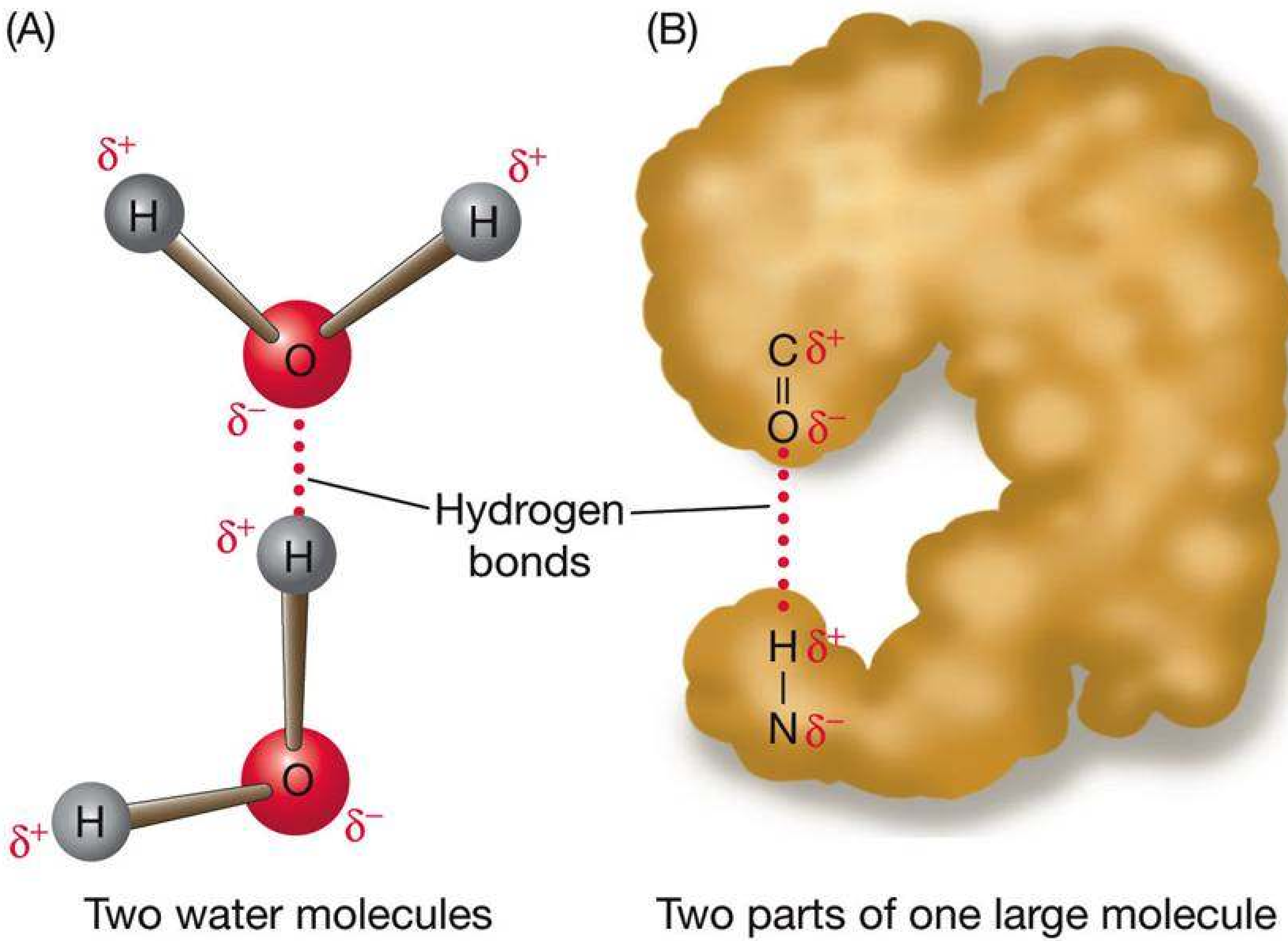



**LIFE 8e, Figure 2.11**

**Hydrogen bonds**: attraction between the $\delta^-$ end of one molecule and the $\delta^+$ hydrogen end of another molecule

Hydrogen bonds form between water molecules, and are important in the structure of DNA and proteins.

# Figure 2.12 Hydrogen Bonds Can Form Between or Within Molecules




**LIFE 8e, Figure 2.12**

Polar molecules that form hydrogen bonds with water are **hydrophylic** (“water-loving”).

Nonpolar molecules such as hydrocarbons that interact with each other, but not with water are **hydrophobic** (“water-hating”).

## 2.2 How Do Atoms Bond to Form Molecules?

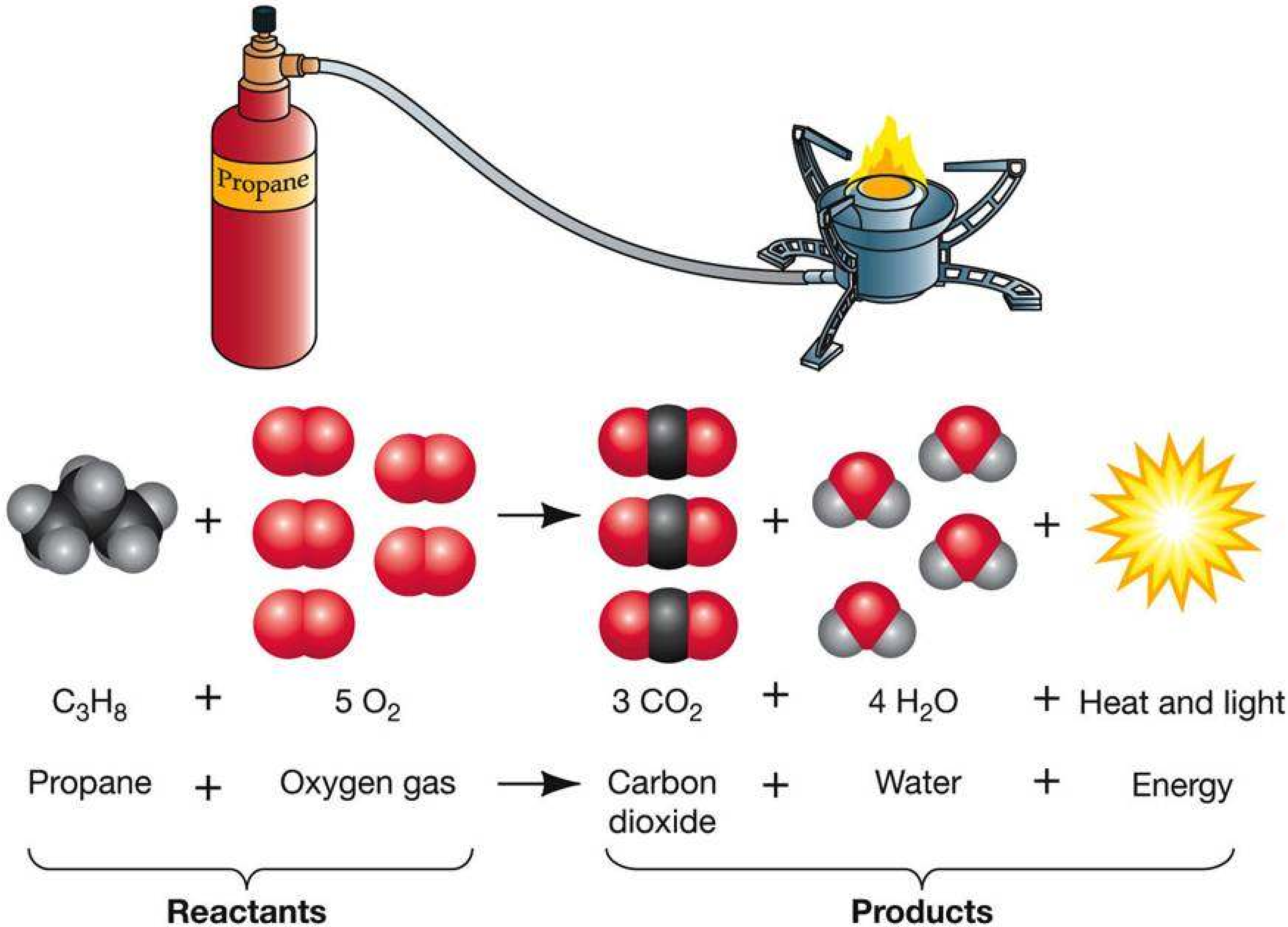
**van der Waals forces**: attractions between nonpolar molecules. They result from random variations in electron distribution.

Individual interactions are brief and weak, but summed over a large molecule, can be substantial.

## 2.3 How Do Atoms Change Partners in Chemical Reactions?

**Chemical reactions**: atoms bond or change bonding partners

# Figure 2.13 Bonding Partners and Energy May Change in a Chemical Reaction




LIFE 8e, Figure 2.13

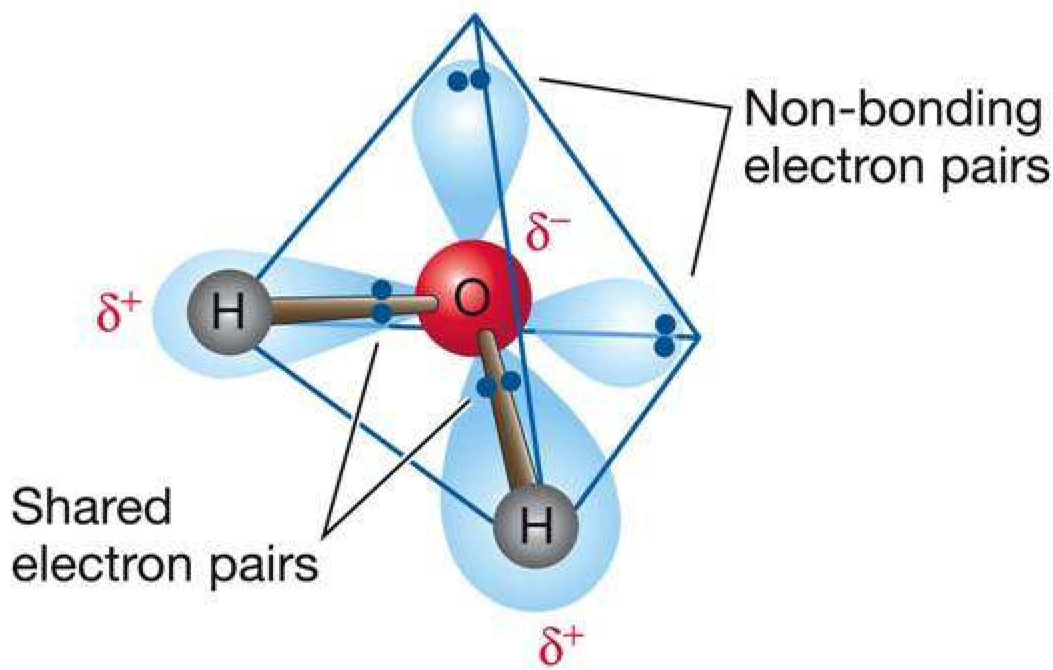
In all chemical reactions, matter and energy are neither created or destroyed.

**Energy:** capacity to do work, or the capacity for change. Energy usually changes form during chemical reactions.

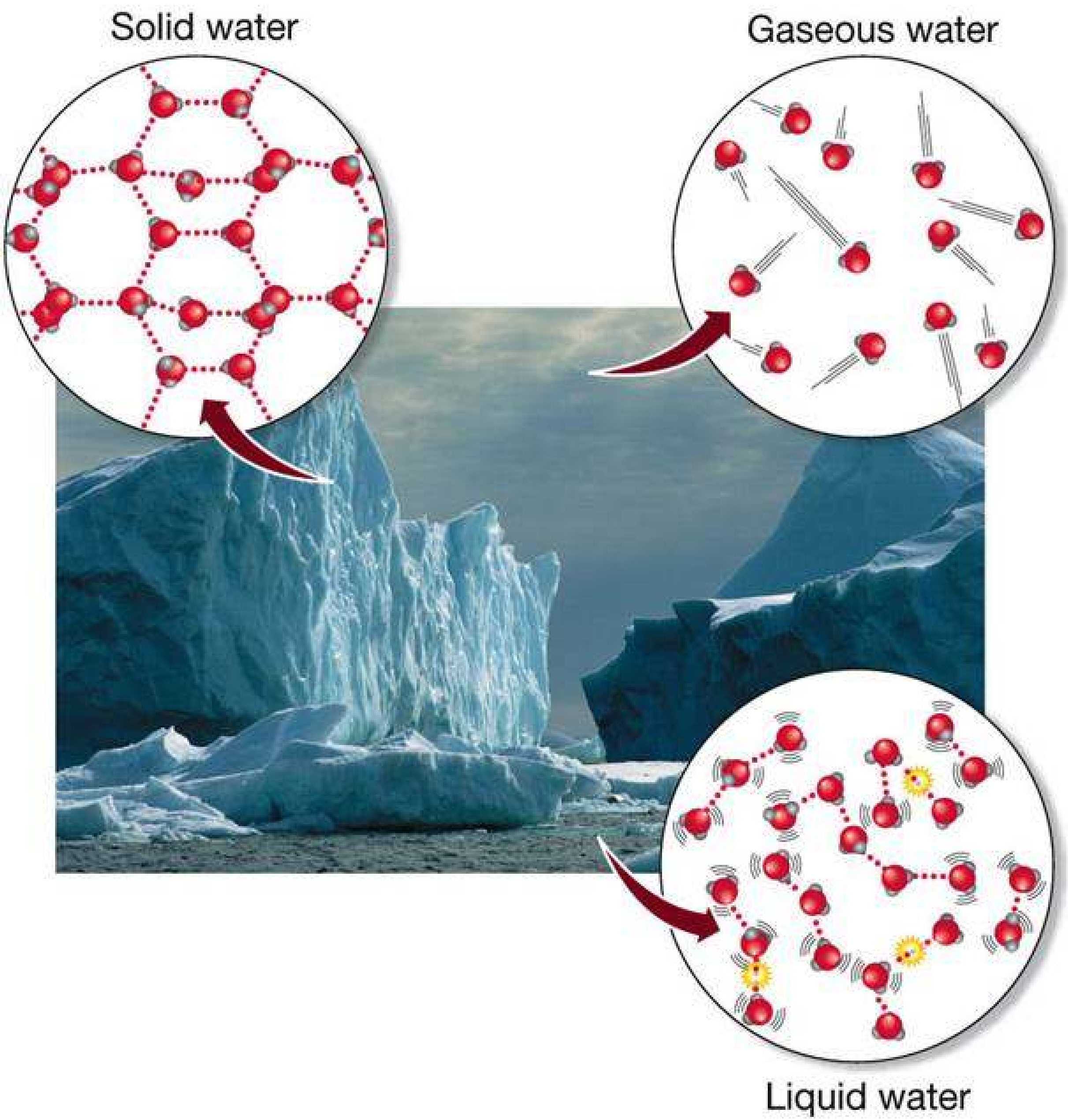
# 2.4 What Properties of Water Make It So Important in Biology?

Water: unique structure and special properties

A polar molecule that forms hydrogen bonds, it has a tetrahedral shape.



# Figure 2.14 Hydrogen Bonds Hold Water Molecules Together




LIFE 8e, Figure 2.14

## 2.4 What Properties of Water Make It So Important in Biology?

Water has high **specific heat**—the amount of heat energy required to raise the temperature of 1 gram of water by 1° C.

Water helps moderate climate because of its high *heat capacity*.

# 2.4 What Properties of Water Make It So Important in Biology?

Water has a high **heat of vaporization**—the amount of heat energy required to change water from a liquid to a gas state.

The basis of evaporative cooling—heat must be absorbed from the environment in contact with the water.

**Cohesion**: water molecules resist coming apart from one another.

- Helps water move through plants.
- Results in *surface tension*.

# 2.4 What Properties of Water Make It So Important in Biology?

A **solution** is a substance (**solute**) dissolved in a liquid (**solvent**).

Many important biochemical reactions occur in *aqueous solutions*.

# 2.4 What Properties of Water Make It So Important in Biology?

*Qualitative analysis*: substances dissolved in water and chemical reactions that occur there

*Quantitative analysis*: measuring concentrations of solutes

**Mole**: The amount of substance (in grams), the mass of which is numerically equal to its molecular weight.

1 mole of $Na^+$ = 23 g

1 mole of $H_2$ = 2 g

One mole contains $6.02 \times 10^{23}$ molecules —**Avogadro's number**

# 2.4 What Properties of Water Make It So Important in Biology?

A 1 molar solution (1*M*) is 1 mole of a substance dissolved in water to make 1 liter of solution.

# Laboratory Technique for Lab 1

We will now learn how to make a molar solution.

Grams of solute = MW(g) x Vol(L) x Molarity

Make the following solutions:

1. 300ml of a 0.3M solution of sucrose
2. 500ml of a 4M solution of NaCl
3. 1000ml of a 1M solution of $CaCl_2$

When **acids** dissolve in water, they release hydrogen ions—$H^+$ (protons).

$H^+$ ions can attach to other molecules and change their properties.

**Bases** accept $H^+$ ions.

# 2.4 What Properties of Water Make It So Important in Biology?

$$HCl \rightarrow H^{+} + Cl^{-}$$

HCl is a *strong acid*—the dissolution is complete.

Organic acids have a carboxyl group:

$$-COOH \rightarrow -COOH^{-} + H^{+}$$

*Weak acids*: not all the acid molecules dissociate into ions.

## 2.4 What Properties of Water Make It So Important in Biology?

NaOH is a *strong base*.

$$NaOH \rightarrow Na^{+} + OH^{-}$$

The $OH^{-}$ absorbs $H^{+}$ to form water.

*Weak bases*:

- Bicarbonate ion

$$HCO_3^- + H^+ \rightarrow H_2CO_3$$

- Ammonia

$$NH_3 + H^+ \rightarrow NH_4^+$$

- Compounds with amino groups

$$-NH_2 + H^+ \rightarrow NH_3^+$$

Acid-base reactions may be reversible.

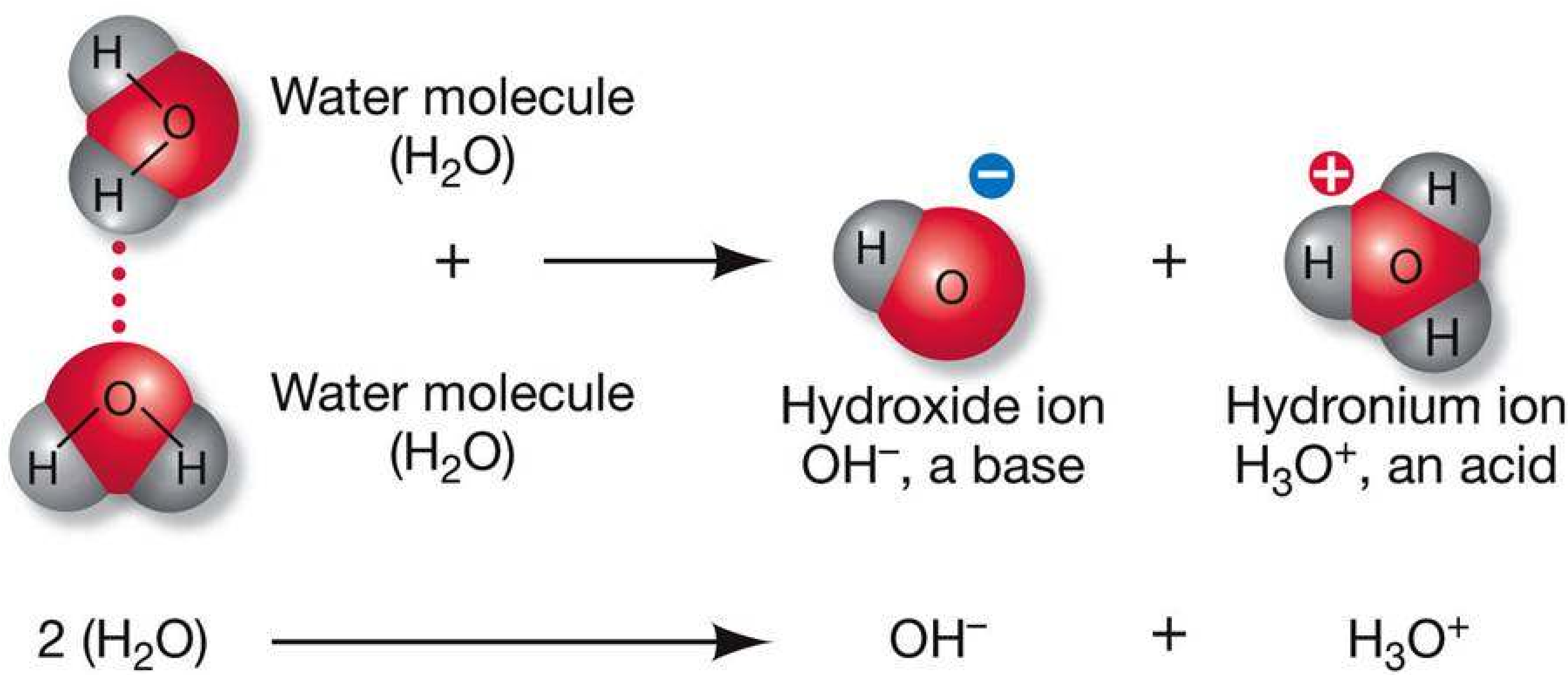
$$CH_3COOH \leftrightarrow CH_3COO^- + H^+$$

Ionization of strong acids and bases is irreversible.

Ionization of weak acids and bases is somewhat reversible.

Water is a weak acid.

$$H_2O \rightarrow H^+ + OH^-$$

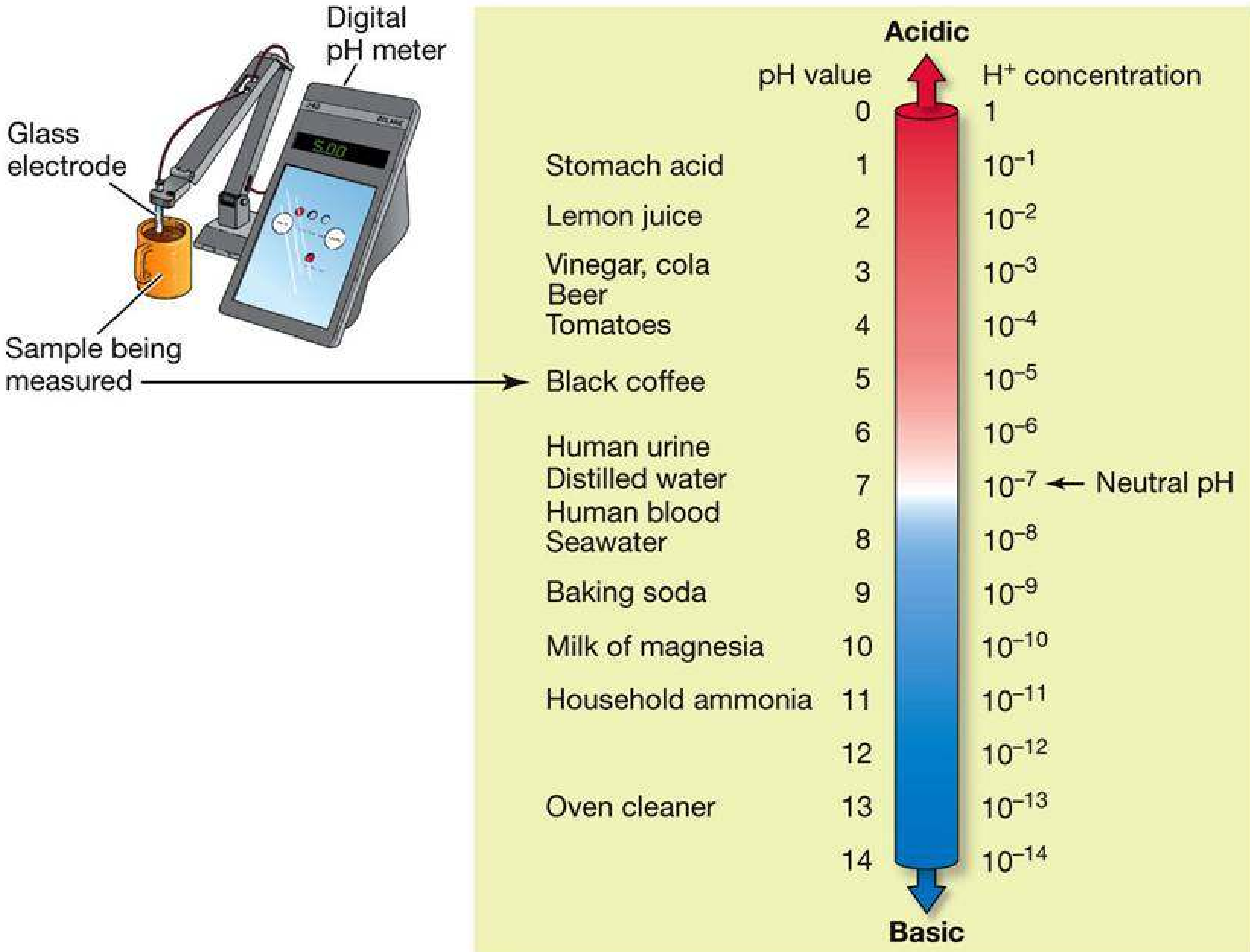


**pH** = negative log of the molar concentration of $H^+$ ions.

$H^+$ concentration of pure water is $10^{-7}$ *M,* its pH = 7.

Lower pH numbers mean higher $H^+$ concentration, or greater acidity.

# Figure 2.16 pH Values of Some Familiar Substances




***LIFE* 8e, Figure 2.16**

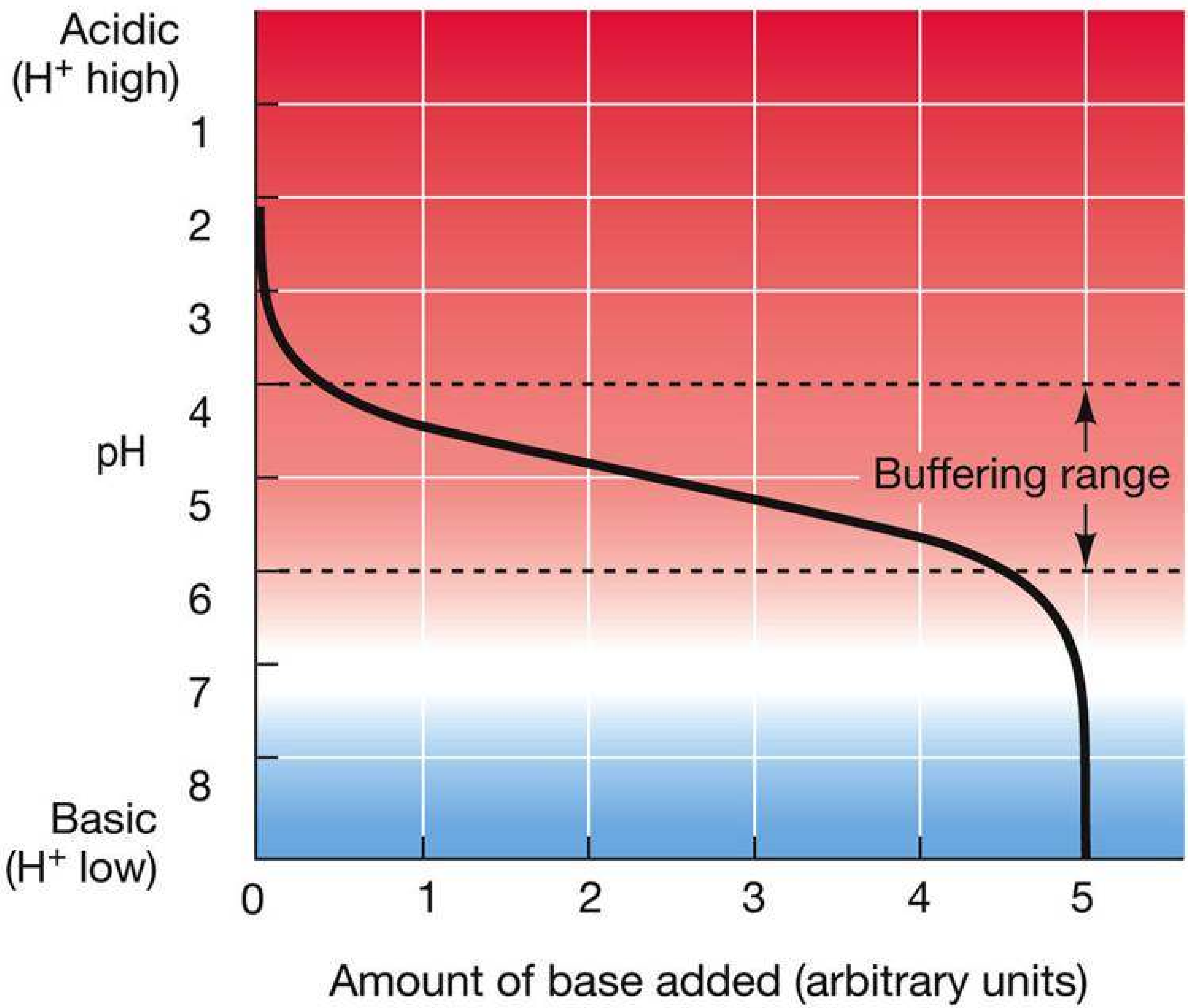
Living organisms maintain constant internal conditions, including pH.

Buffers help maintain constant pH.

A **buffer** is a weak acid and its corresponding base.

$$HCO_3 + H^+ \rightarrow H_2CO_3$$

# Figure 2.17 Buffers Minimize Changes in pH




**LIFE 8e, Figure 2.17**

Buffers illustrate the *law of mass action*: addition of reactant on one side of a reversible equation drives the system in the direction that uses up that compound.

## 2.4 What Properties of Water Make It So Important in Biology?

Life's chemistry began in water.

Water and other chemicals may have come to Earth on comets.

Water was an essential condition for life to evolve.