CAMPBELL

BIOLOGY

TENTH EDITION

Reece • Urry • Cain • Wasserman • Minorsky • Jackson

2

The Chemical Context of Life

Lecture Presentation by
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Kathleen Fitzpatrick

A Chemical Connection to Biology

- Biology is the study of life
- Living organisms and their environments are subject to basic laws of physics and chemistry
- One example is the use of formic acid by ants to protect themselves against predators and microbial parasites

Figure 2.1

Figure 2.1a

Concept 2.1: Matter consists of chemical elements in pure form and in combinations called compounds

- Organisms are composed of **matter**
- Matter is anything that takes up space and has mass

Elements and Compounds

- Matter is made up of elements
- An **element** is a substance that cannot be broken down to other substances by chemical reactions
- A **compound** is a substance consisting of two or more elements in a fixed ratio
- A compound has characteristics different from those of its elements

Figure 2.2

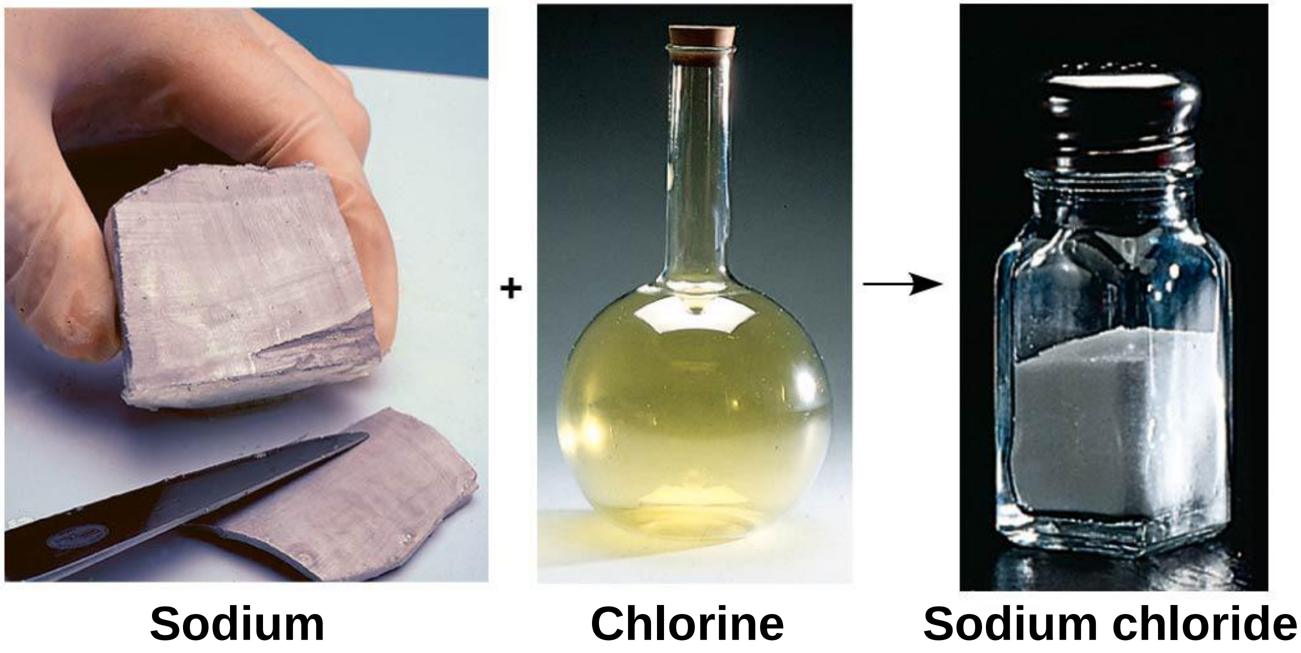
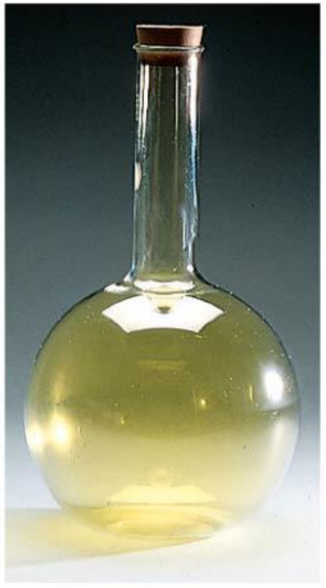


Figure 2.2a

Sodium

Figure 2.2b



Chlorine

Figure 2.2c

Sodium chloride

The Elements of Life

- About 20–25% of the 92 elements are essential to life **(essential elements)**
- Carbon, hydrogen, oxygen, and nitrogen make up 96% of living matter
- Most of the remaining 4% consists of calcium, phosphorus, potassium, and sulfur
- **Trace elements** are those required by an organism in only minute quantities

Table 2.1

Table 2.1 Elements in the Human Body

Element	Symbol	Percentage of Body Mass (including water)	
Oxygen	O	65.0%	96.3%
Carbon	C	18.5%	
Hydrogen	H	9.5%	
Nitrogen	N	3.3%	
Calcium	Ca	1.5%	3.7%
Phosphorus	P	1.0%	
Potassium	K	0.4%	
Sulfur	S	0.3%	
Sodium	Na	0.2%	
Chlorine	Cl	0.2%	
Magnesium	Mg	0.1%	

Trace elements (less than 0.01% of mass): Boron (B), chromium (Cr), cobalt (Co), copper (Cu), fluorine (F), iodine (I), iron (Fe), manganese (Mn), molybdenum (Mo), selenium (Se), silicon (Si), tin (Sn), vanadium (V), zinc (Zn)

Case Study: Evolution of Tolerance to Toxic Elements

- Some elements can be toxic, for example, arsenic
- Some species can become adapted to environments containing toxic elements
  - For example, some plant communities are adapted to serpentine

Figure 2.3

Figure 2.3a

Figure 2.3b

Figure 2.3c

Concept 2.2: An element's properties depend on the structure of its atoms

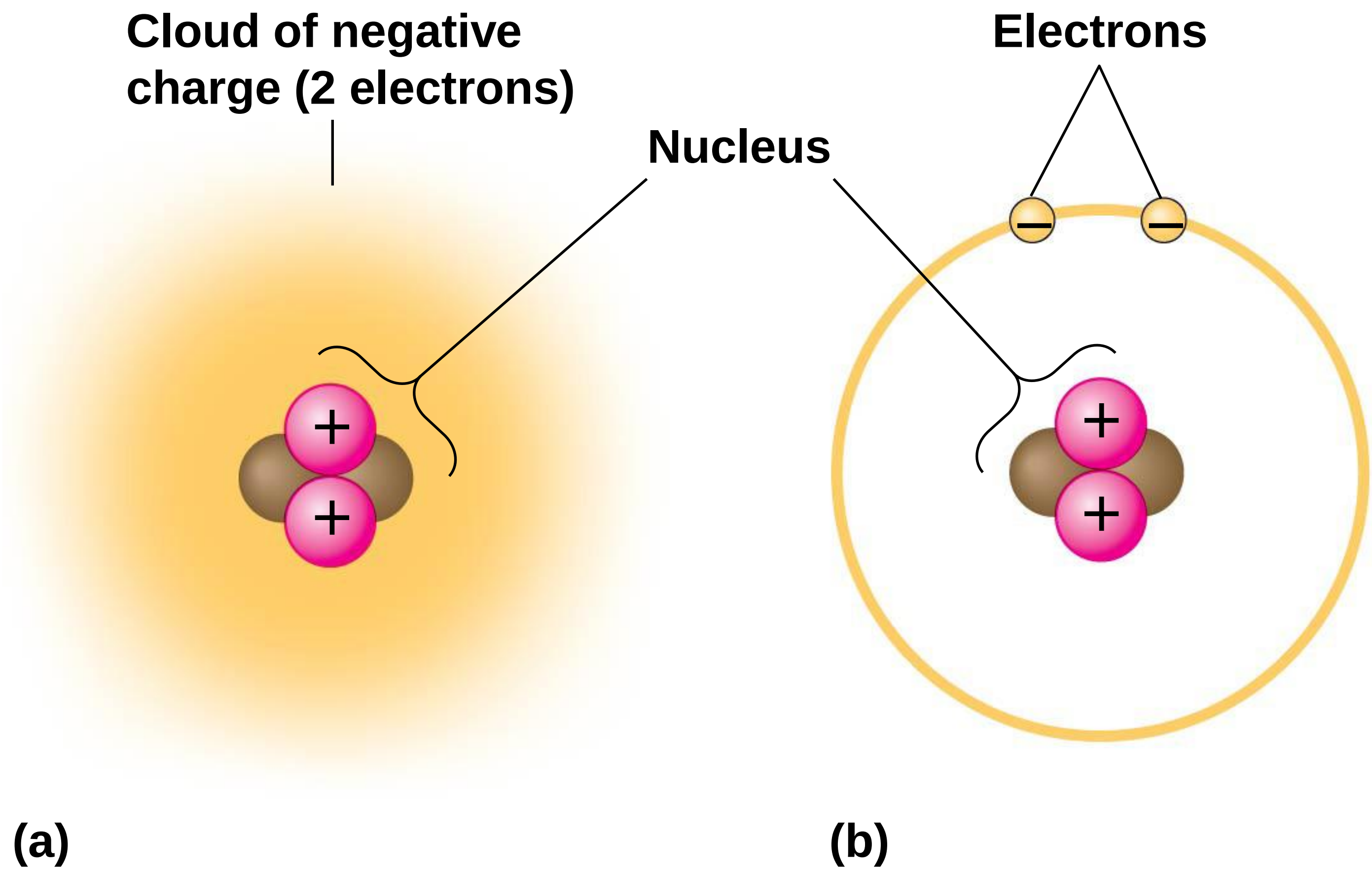
- Each element consists of unique atoms
- An **atom** is the smallest unit of matter that still retains the properties of an element

Subatomic Particles

- Atoms are composed of subatomic particles
- Relevant subatomic particles include
  - **Neutrons** (no electrical charge)
  - **Protons** (positive charge)
  - **Electrons** (negative charge)

- Neutrons and protons form the **atomic nucleus**
- Electrons form a cloud around the nucleus
- Neutron mass and proton mass are almost identical and are measured in **daltons**

Figure 2.4



Atomic Number and Atomic Mass

- Atoms of the various elements differ in number of subatomic particles
- An element's **atomic number** is the number of protons in its nucleus
- An element's **mass number** is the sum of protons plus neutrons in the nucleus
- **Atomic mass**, the atom's total mass, can be approximated by the mass number

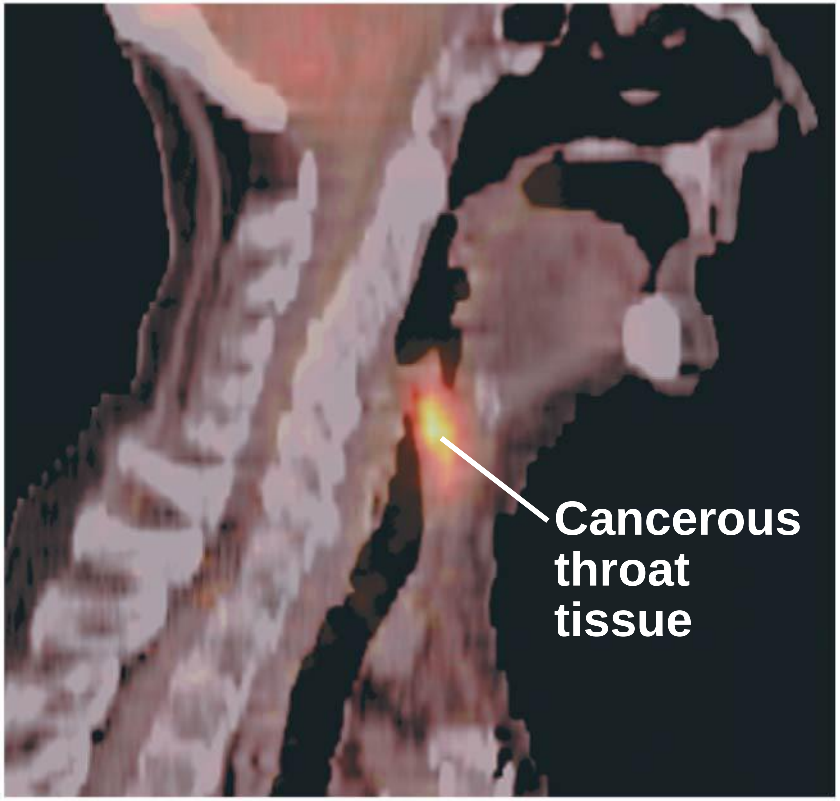
Isotopes

- All atoms of an element have the same number of protons but may differ in number of neutrons
- **Isotopes** are two atoms of an element that differ in number of neutrons
- **Radioactive isotopes** decay spontaneously, giving off particles and energy

Radioactive Tracers

- Radioactive isotopes are often used as diagnostic tools in medicine
- Radioactive tracers can be used to track atoms through metabolism
- They can also be used in combination with sophisticated imaging instruments

Figure 2.5



Radiometric Dating

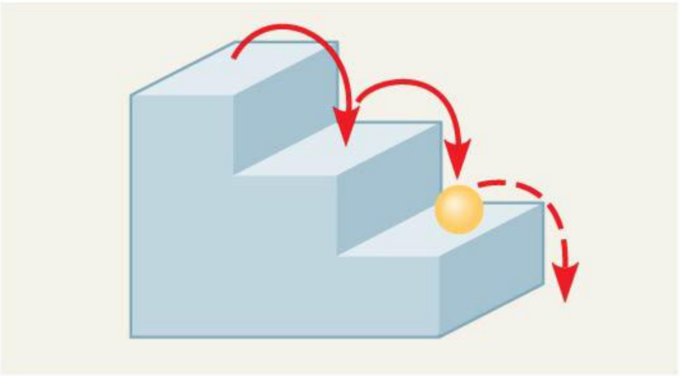
- A “parent” isotope decays into its “daughter” isotope at a fixed rate, expressed as the **half-life**
- In **radiometric dating**, scientists measure the ratio of different isotopes and calculate how many half-lives have passed since the fossil or rock was formed
- Half-life values vary from seconds or days to billions of years

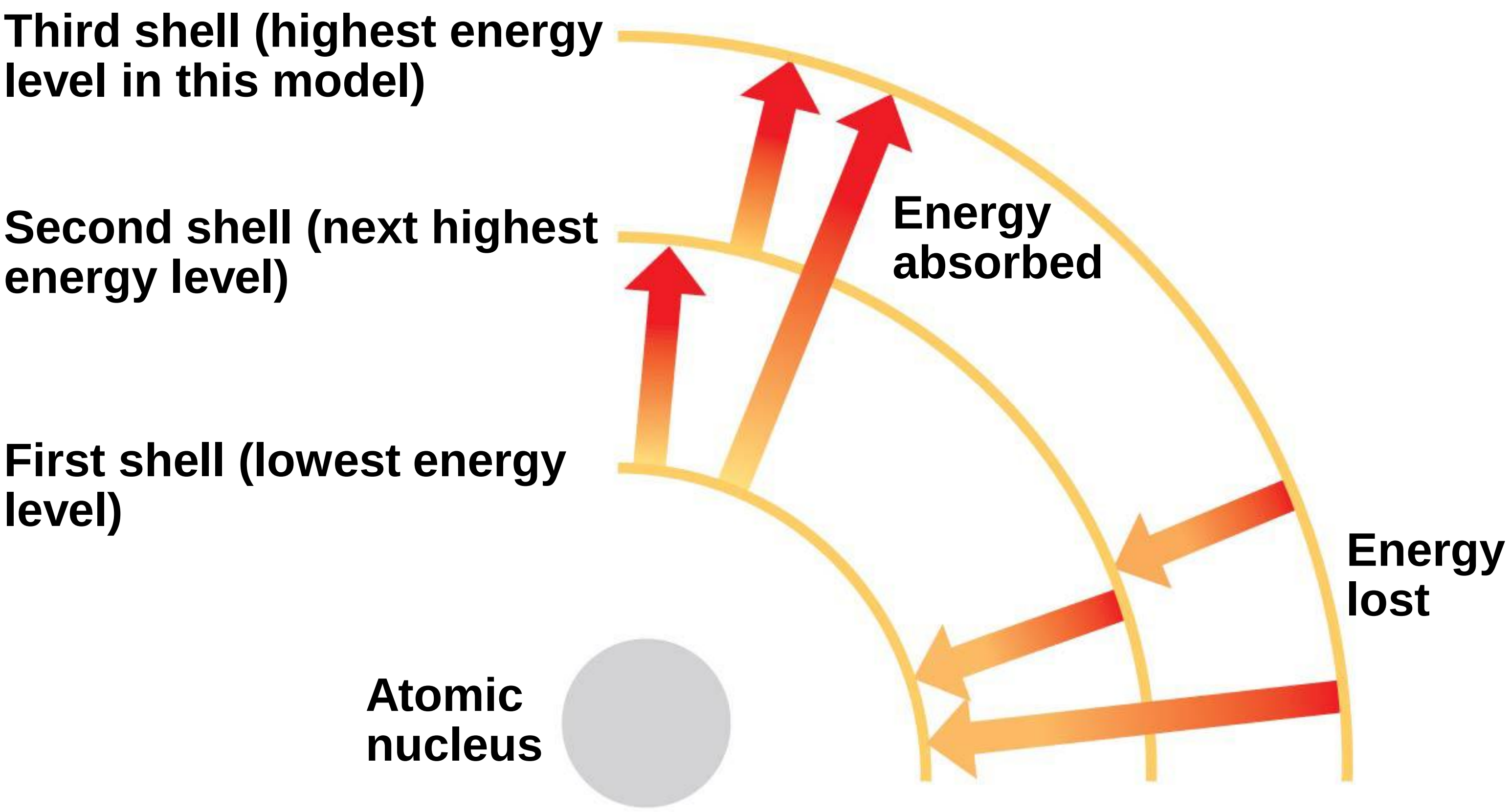
The Energy Levels of Electrons

- **Energy** is the capacity to cause change
- **Potential energy** is the energy that matter has because of its location or structure
- The electrons of an atom differ in their amounts of potential energy
- An electron’s state of potential energy is called its energy level, or **electron shell**

Figure 2.6

(a) A ball bouncing down a flight of stairs provides an analogy for energy levels of electrons.



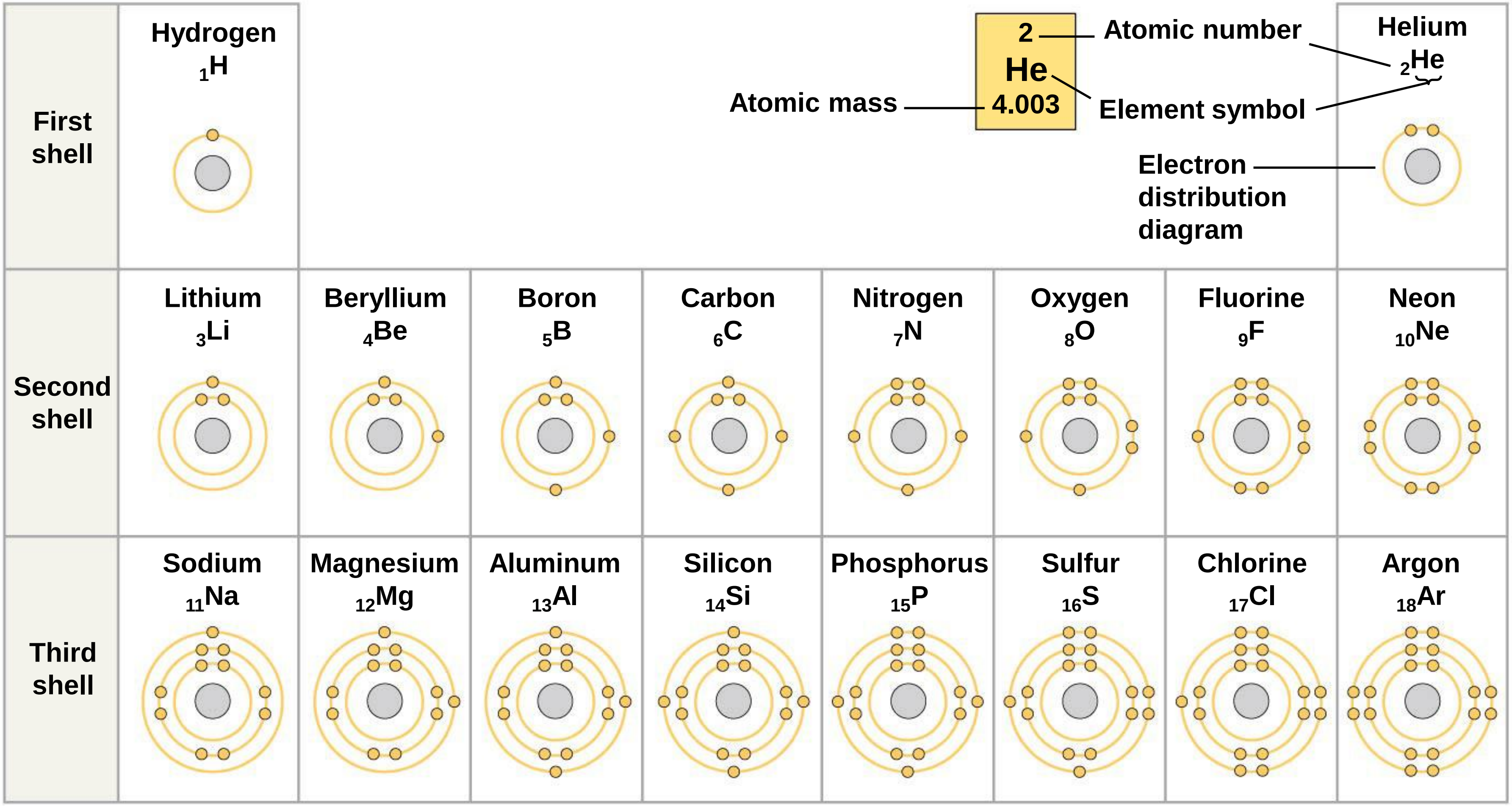


(b)

Electron Distribution and Chemical Properties

- The chemical behavior of an atom is determined by the distribution of electrons in electron shells
- The periodic table of the elements shows the electron distribution for each element

Figure 2.7



First shell
Second shell
Third shell
Hydrogen
$_1H$
2
He
4.003
Atomic number
Atomic mass
Element symbol
Electron distribution diagram
Helium
$_2He$
Lithium
$_3Li$
Beryllium
$_4Be$
Boron
$_5B$
Carbon
$_6C$
Nitrogen
$_7N$
Oxygen
$_8O$
Fluorine
$_9F$
Neon
$_{10}Ne$
Sodium
$_{11}Na$
Magnesium
$_{12}Mg$
Aluminum
$_{13}Al$
Silicon
$_{14}Si$
Phosphorus
$_{15}P$
Sulfur
$_{16}S$
Chlorine
$_{17}Cl$
Argon
$_{18}Ar$

Figure 2.7a

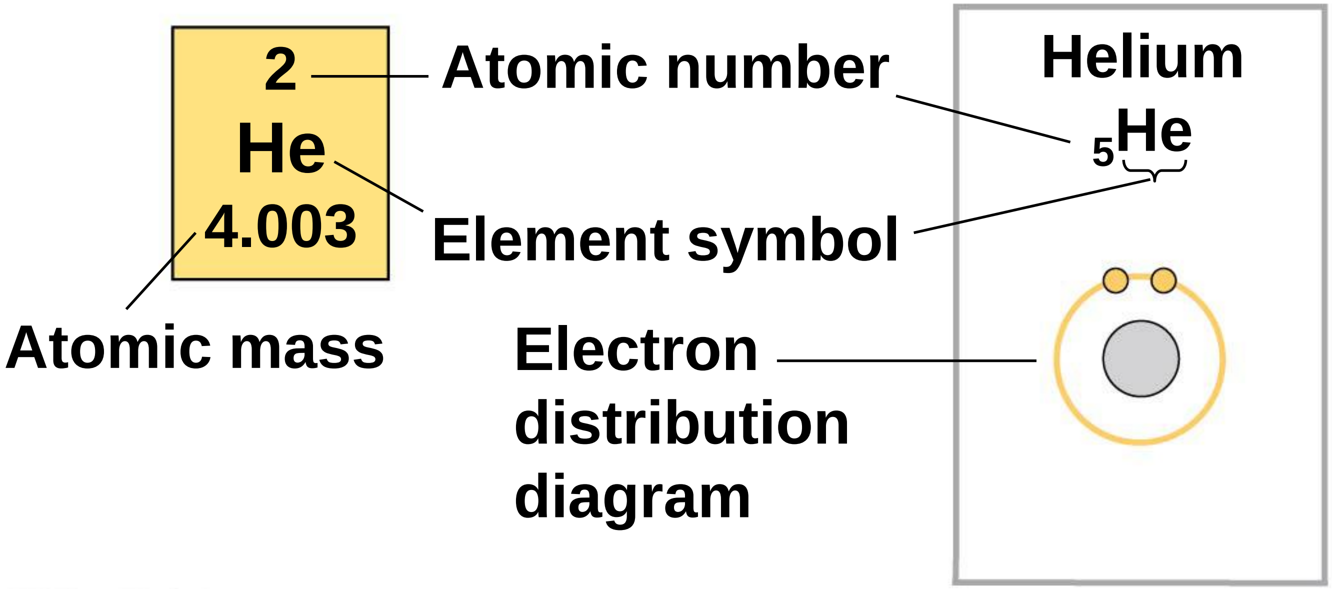

2
He
4.003
Atomic number
Element symbol
Atomic mass
Helium
5He
Electron
distribution
diagram

Figure 2.7b

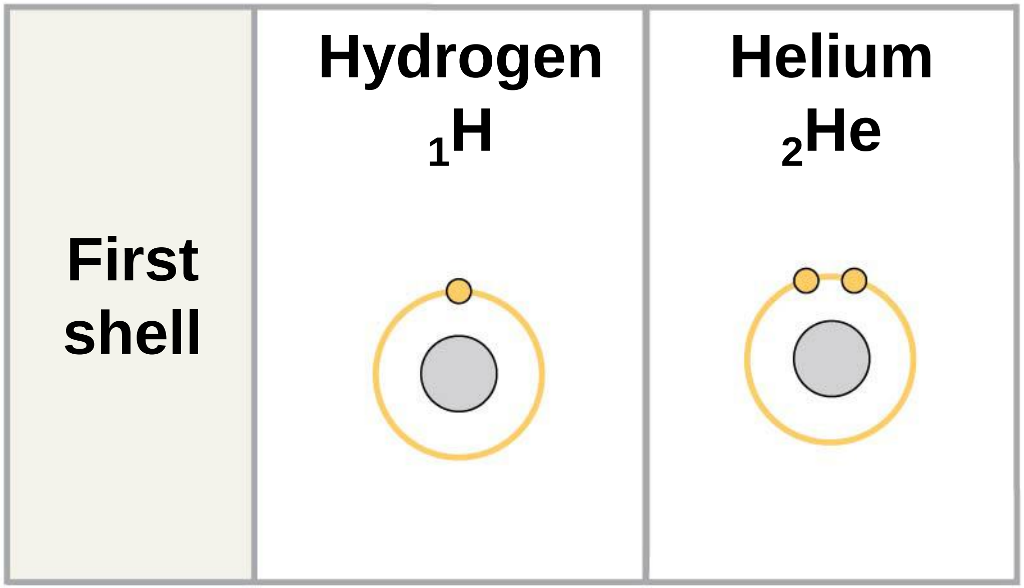
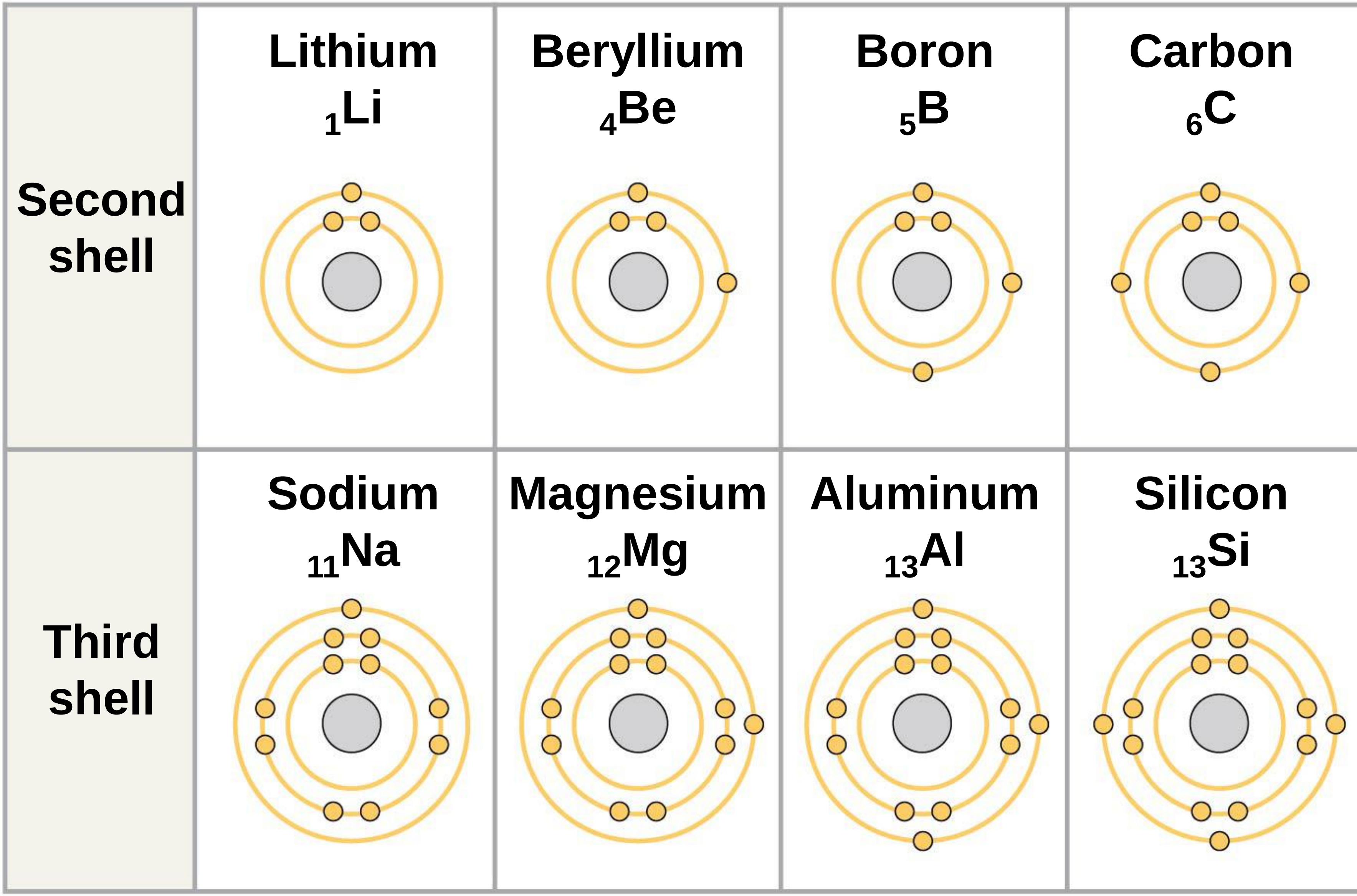
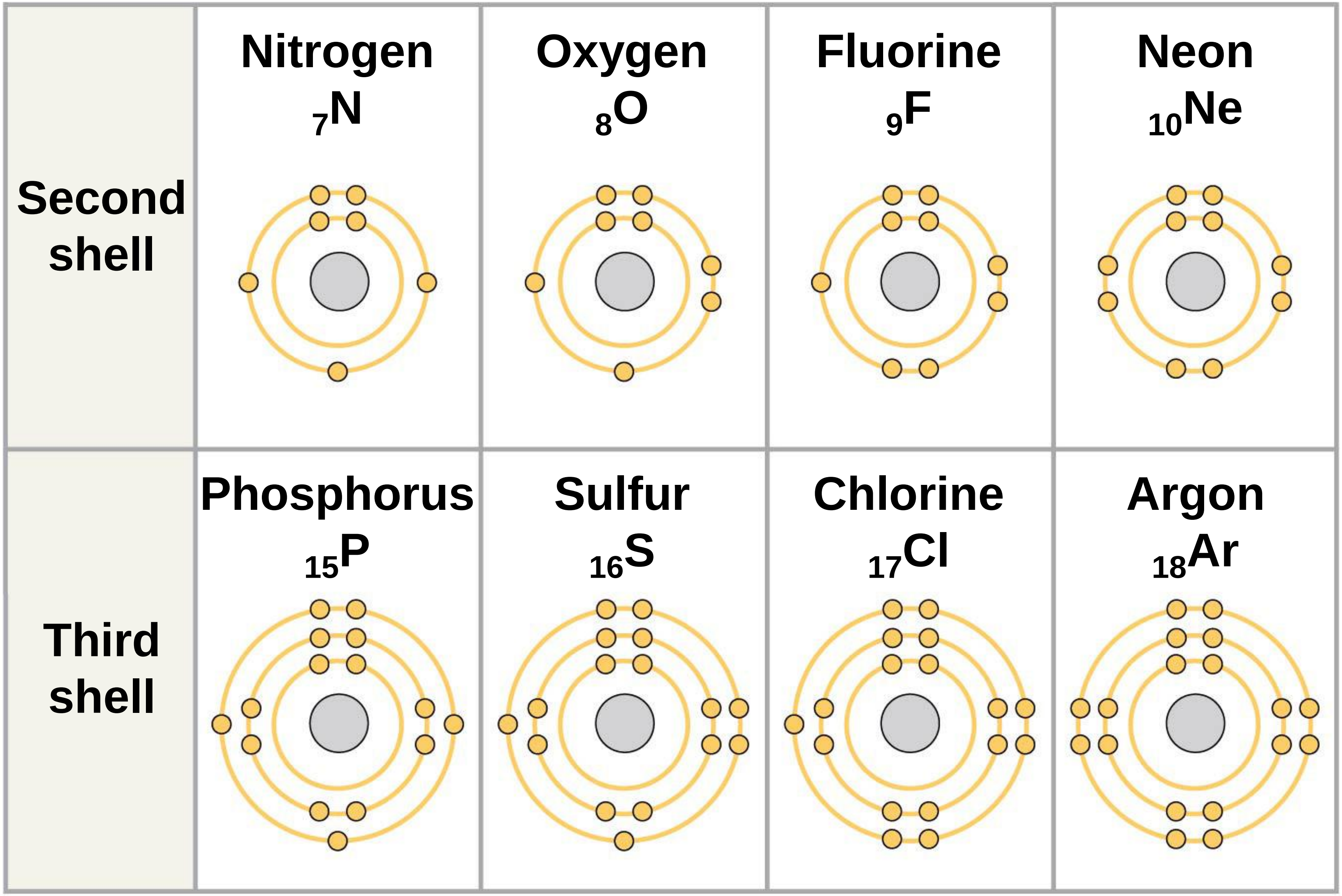


Figure 2.7c



Lithium
$_1Li$
Beryllium
$_4Be$
Boron
$_5B$
Carbon
$_6C$
Second shell
Sodium
$_{11}Na$
Magnesium
$_{12}Mg$
Aluminum
$_{13}Al$
Silicon
$_{13}Si$
Third shell

Figure 2.7d



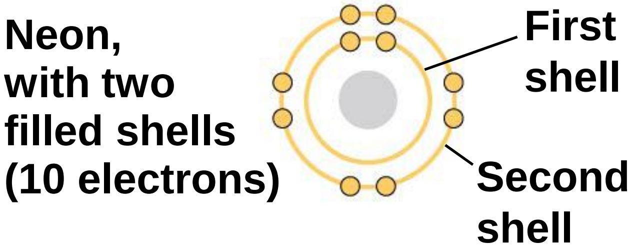
Second shell
Nitrogen
$_{7}N$
Oxygen
$_{8}O$
Fluorine
$_{9}F$
Neon
$_{10}Ne$
Third shell
Phosphorus
$_{15}P$
Sulfur
$_{16}S$
Chlorine
$_{17}Cl$
Argon
$_{18}Ar$

- **Valence electrons** are those in the outermost shell, or **valence shell**
- The chemical behavior of an atom is mostly determined by the valence electrons
- Elements with a full valence shell are chemically inert

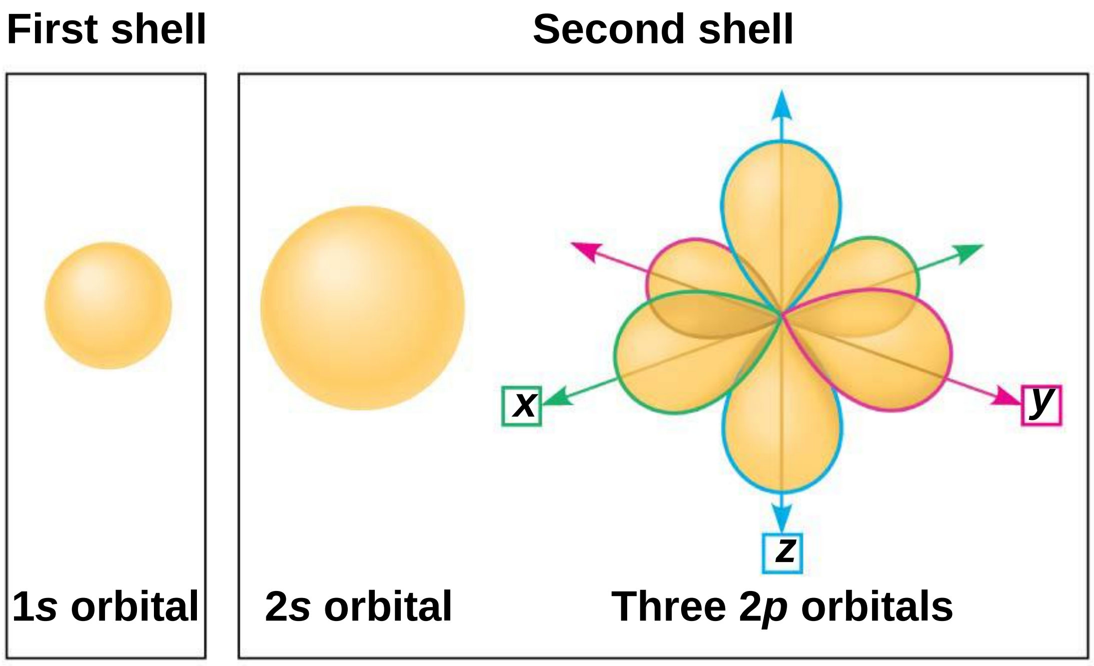
Electron Orbitals

- An **orbital** is the three-dimensional space where an electron is found 90% of the time
- Each electron shell consists of a specific number of orbitals

Figure 2.8



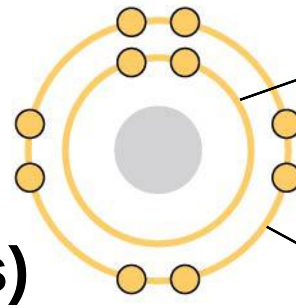
(a) Electron distribution diagram



(b) Separate electron orbitals

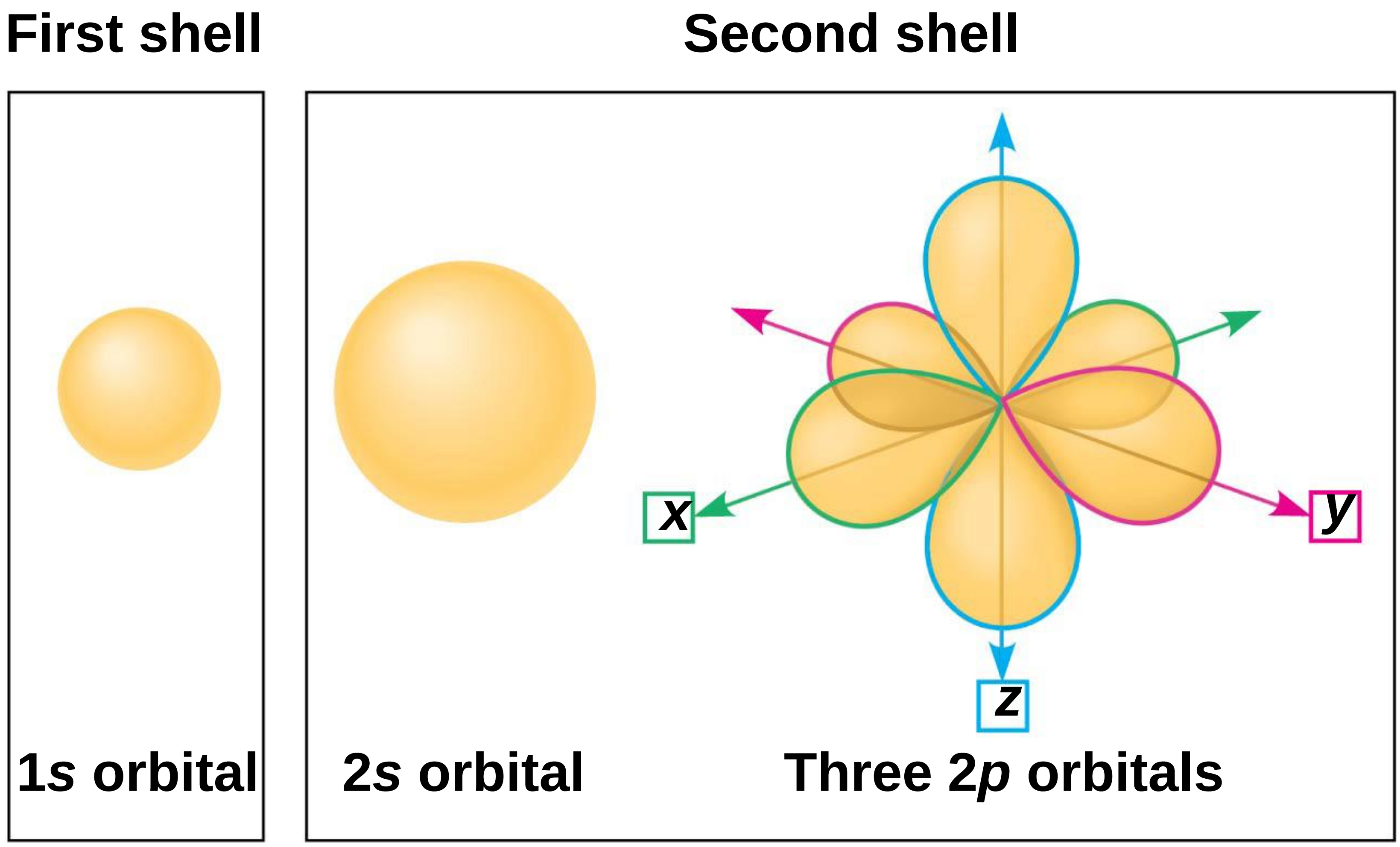
(c) Superimposed electron orbitals

Figure 2.8a

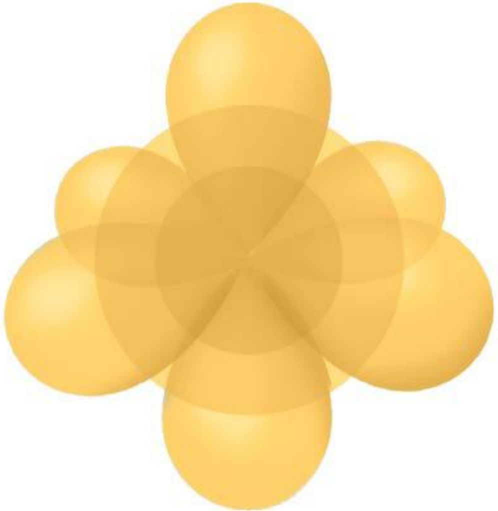


(a) Electron distribution diagram

Figure 2.8b



(b) Separate electron orbitals



(c) Superimposed electron orbitals

Concept 2.3: The formation and function of molecules depend on chemical bonding between atoms

- Atoms with incomplete valence shells can share or transfer valence electrons with certain other atoms
- These interactions usually result in atoms staying close together, held by attractions called **chemical bonds**

Covalent Bonds

- A **covalent bond** is the sharing of a pair of valence electrons by two atoms
- In a covalent bond, the shared electrons count as part of each atom's valence shell

Figure 2.9-1

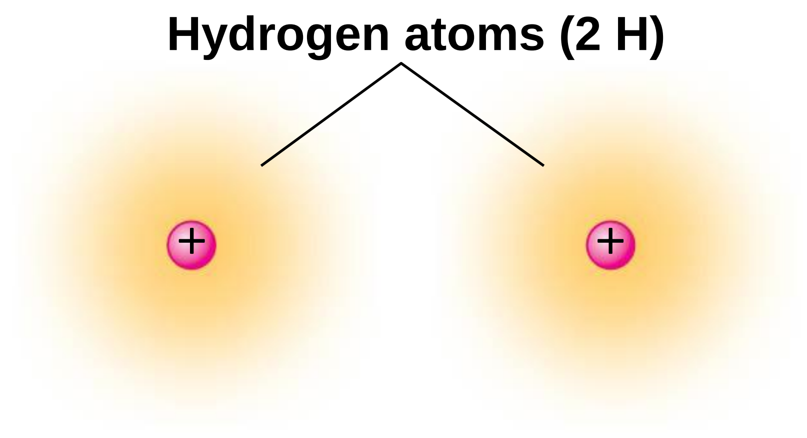


Figure 2.9-2

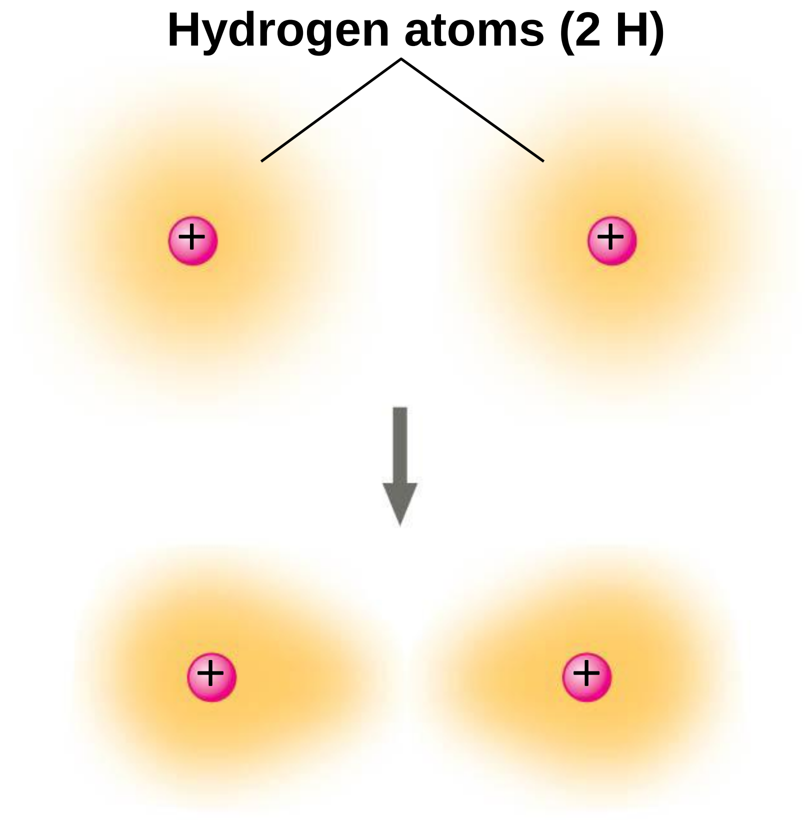
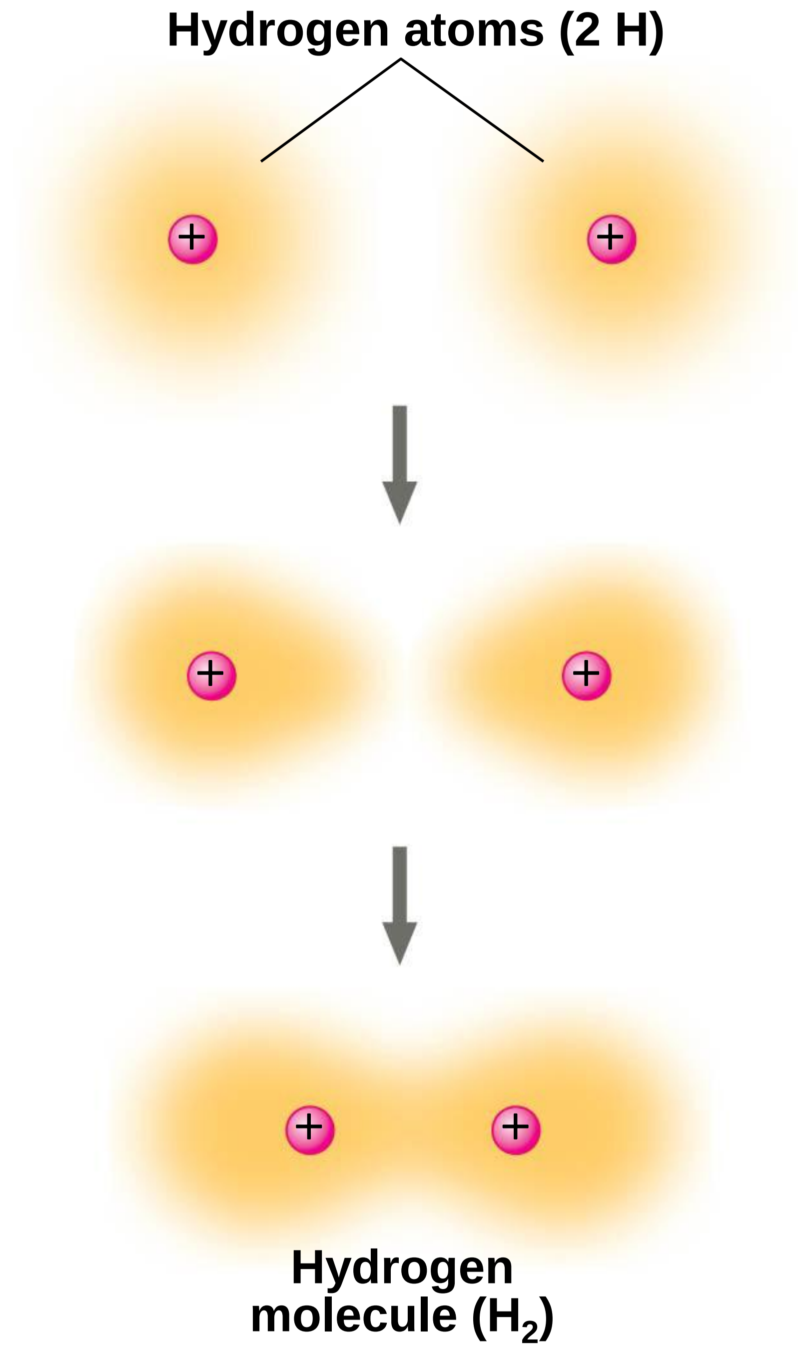


Figure 2.9-3



- A **molecule** consists of two or more atoms held together by covalent bonds
- A single covalent bond, or **single bond**, is the sharing of one pair of valence electrons
- A double covalent bond, or **double bond**, is the sharing of two pairs of valence electrons

- The notation used to represent atoms and bonding is called a **structural formula**
  - For example, H—H
- This can be abbreviated further with a **molecular formula**
  - For example, H_2

Figure 2.10

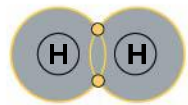
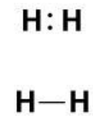
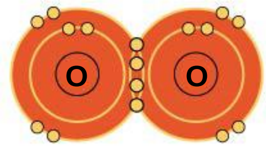
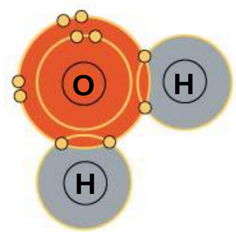
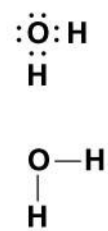
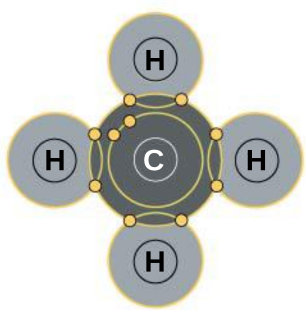
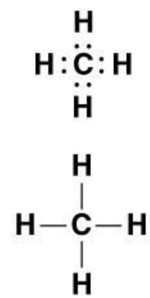
Name and Molecular Formula	Electron Distribution Diagram	Lewis Dot Structure and Structural Formula	Space-Filling Model
(a) Hydrogen (H_2)			
(b) Oxygen (O_2)			
(c) Water (H_2O)			
(d) Methane (CH_4)			

Figure 2.10a

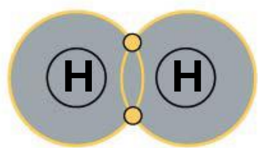
Name and Molecular Formula	Electron Distribution Diagram	Lewis Dot Structure and Structural Formula	Space-Filling Model
(a) Hydrogen (H_2)		H:H H—H	

Figure 2.10b

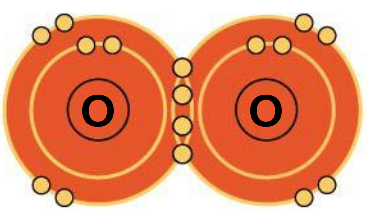
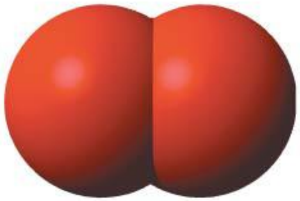
Name and Molecular Formula	Electron Distribution Diagram	Lewis Dot Structure and Structural Formula	Space-Filling Model
(b) Oxygen (O_2)			

Figure 2.10c

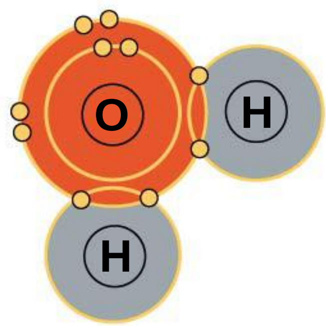
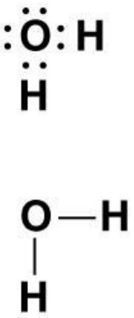
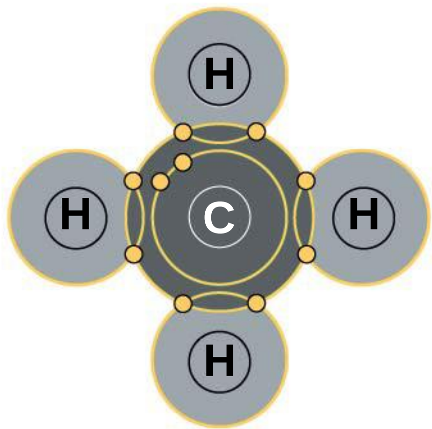
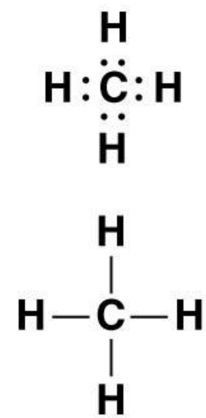
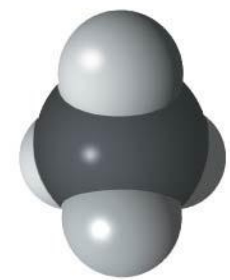
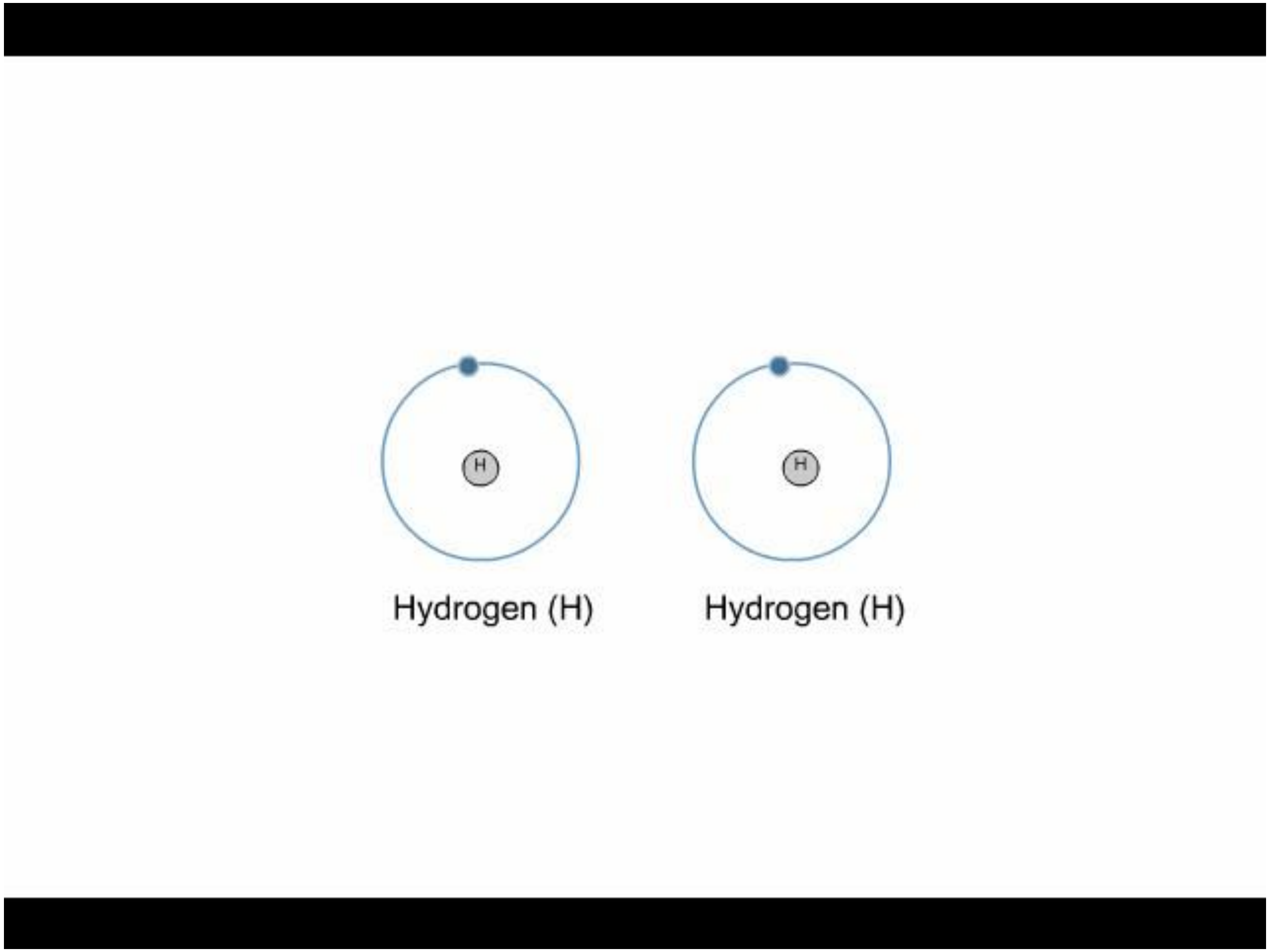
Name and Molecular Formula	Electron Distribution Diagram	Lewis Dot Structure and Structural Formula	Space-Filling Model
(c) Water (H_2O)			

Figure 2.10d

Name and Molecular Formula	Electron Distribution Diagram	Lewis Dot Structure and Structural Formula	Space-Filling Model
(d) Methane (CH_4)			

Animation: Covalent Bonds

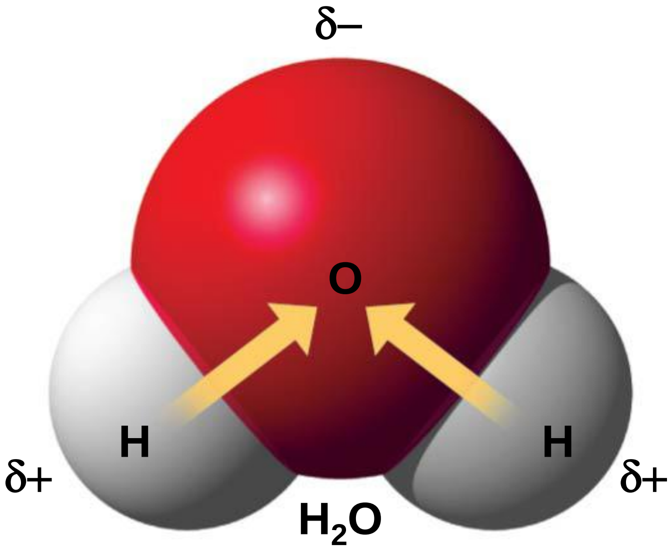


- Covalent bonds can form between atoms of the same element or atoms of different elements
- A compound is a combination of two or more different elements
- Bonding capacity is called the atom's **valence**

- Atoms in a molecule attract electrons to varying degrees
- **Electronegativity** is an atom’s attraction for the electrons in a covalent bond
- The more electronegative an atom, the more strongly it pulls shared electrons toward itself

- In a **nonpolar covalent bond**, the atoms share the electron equally
- In a **polar covalent bond**, one atom is more electronegative, and the atoms do not share the electron equally
- Unequal sharing of electrons causes a partial positive or negative charge for each atom or molecule

Figure 2.11



Ionic Bonds

- Atoms sometimes strip electrons from their bonding partners
- An example is the transfer of an electron from sodium to chlorine
- After the transfer of an electron, both atoms have charges
- A charged atom (or molecule) is called an **ion**

Figure 2.12-1

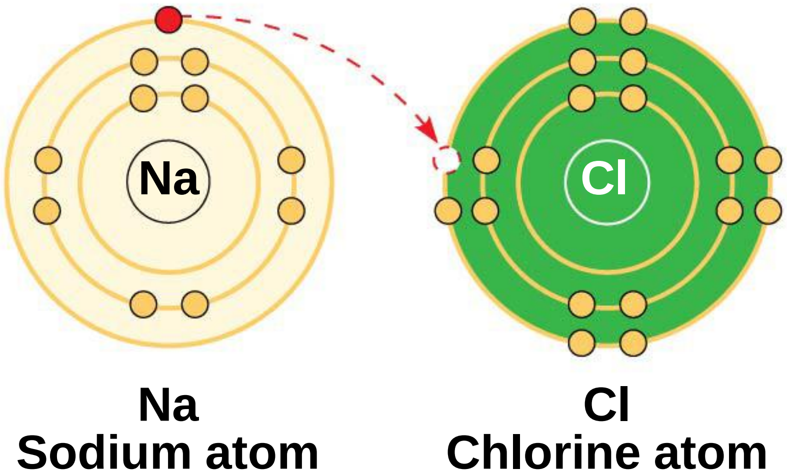
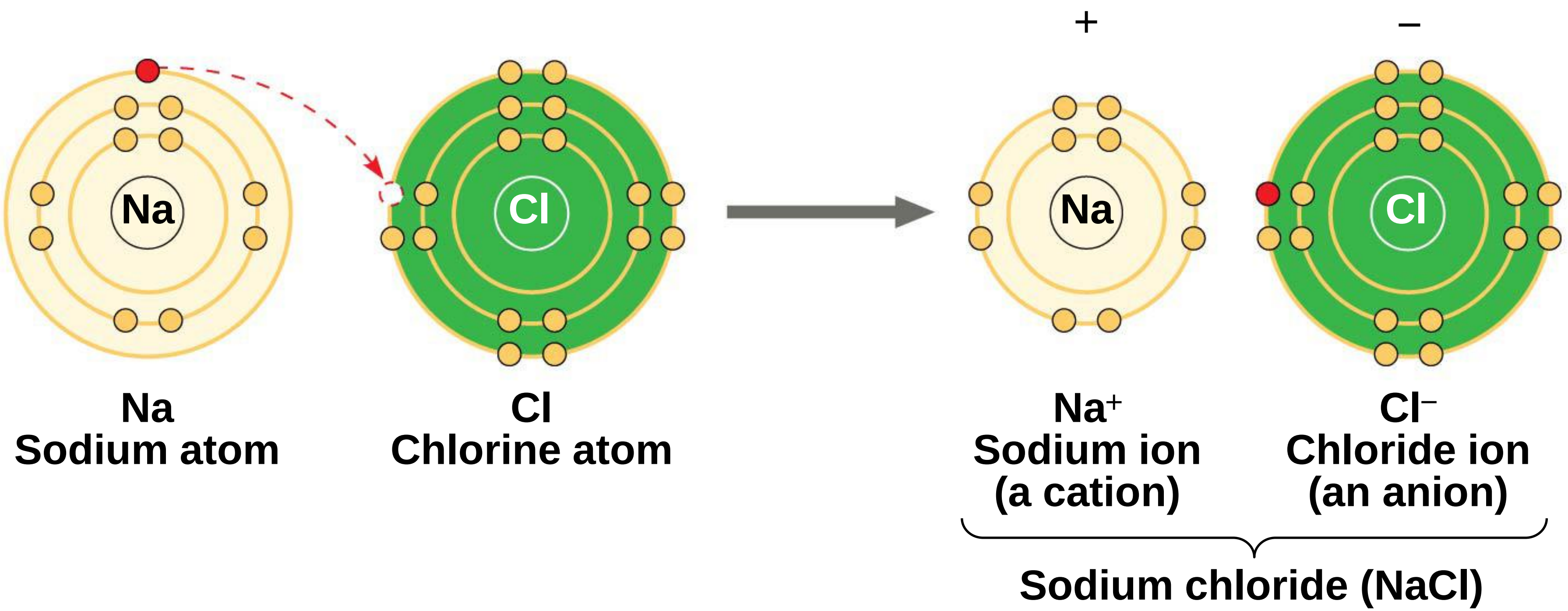
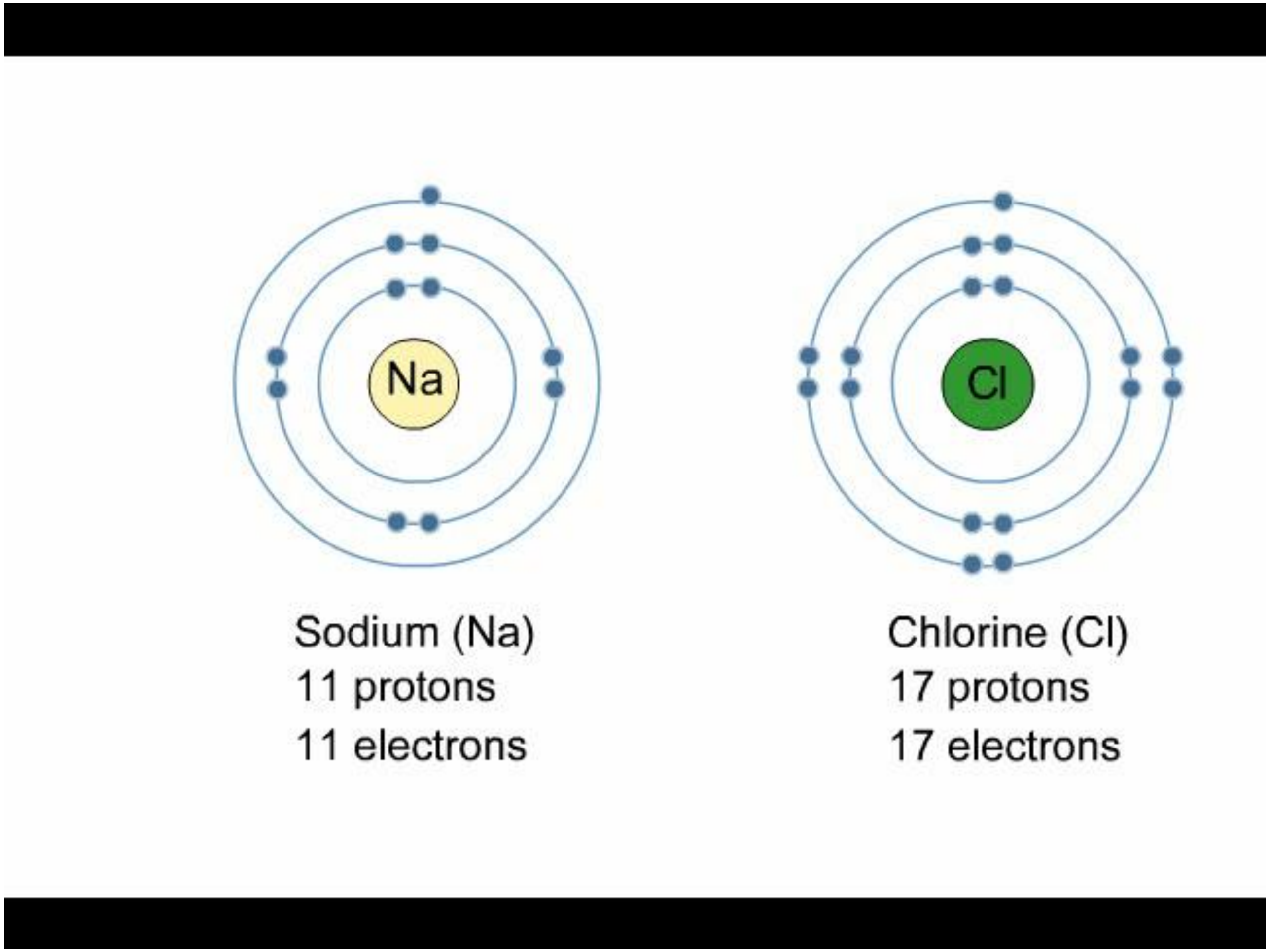


Figure 2.12-2



+
–
Na
Cl
Na
Cl
Na
Sodium atom
Cl
Chlorine atom
Na+
Sodium ion
(a cation)
Cl–
Chloride ion
(an anion)
Sodium chloride (NaCl)

Animation: Ionic Bonds



- A **cation** is a positively charged ion
- An **anion** is a negatively charged ion
- An **ionic bond** is an attraction between an anion and a cation

- Compounds formed by ionic bonds are called **ionic compounds**, or **salts**
- Salts, such as sodium chloride (table salt), are often found in nature as crystals

Figure 2.13

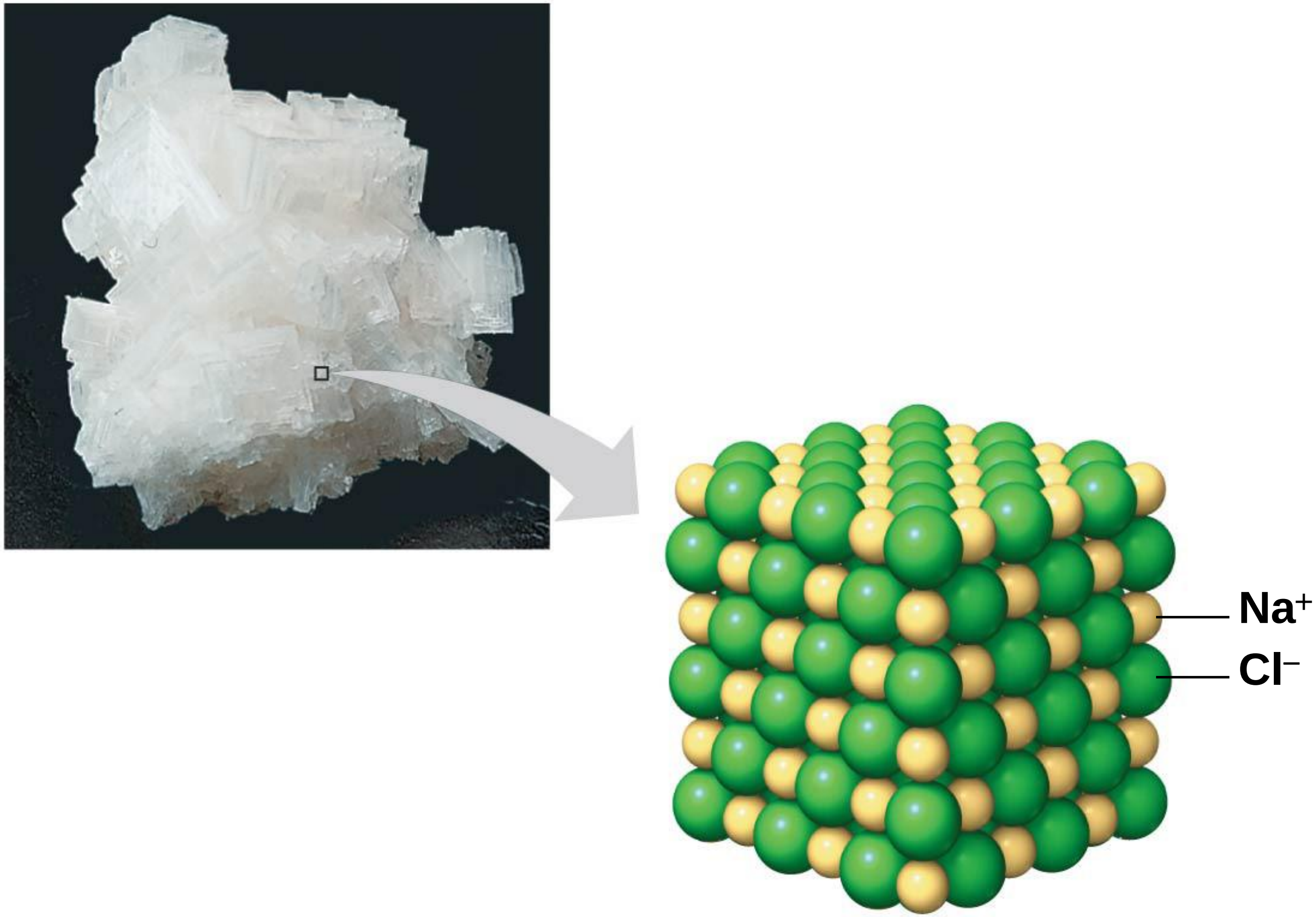


Figure 2.13a

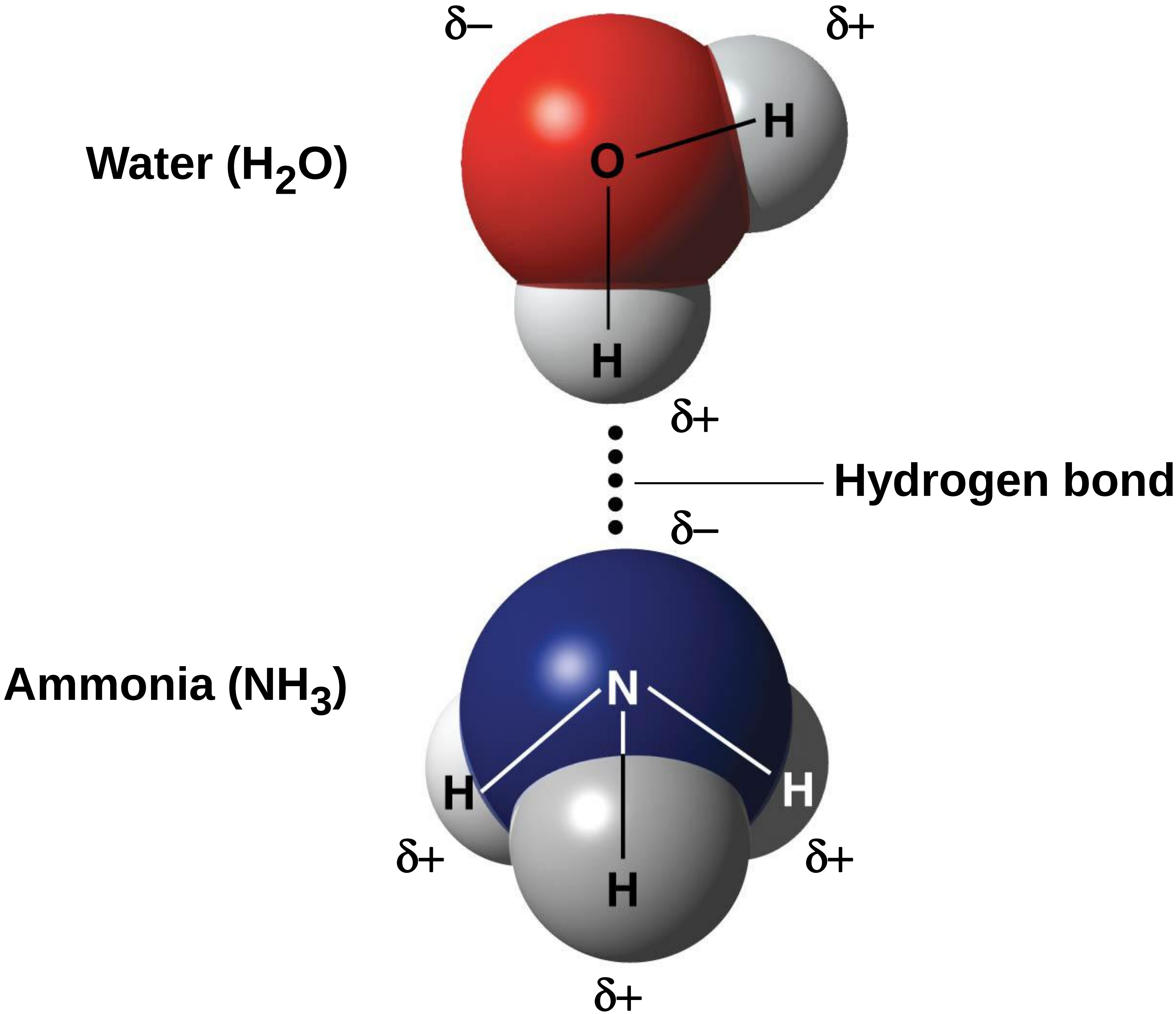
Weak Chemical Bonds

- Most of the strongest bonds in organisms are covalent bonds that form a cell's molecules
- Weak chemical bonds are also indispensable
- Many large biological molecules are held in their functional form by weak bonds
- The reversibility of weak bonds can be an advantage

Hydrogen Bonds

- A **hydrogen bond** forms when a hydrogen atom covalently bonded to one electronegative atom is also attracted to another electronegative atom
- In living cells, the electronegative partners are usually oxygen or nitrogen atoms

Figure 2.14



Van der Waals Interactions

- If electrons are distributed asymmetrically in molecules or atoms, they may accumulate by chance in one part of a molecule
- **Van der Waals interactions** are attractions between molecules that are close together as a result of these charges

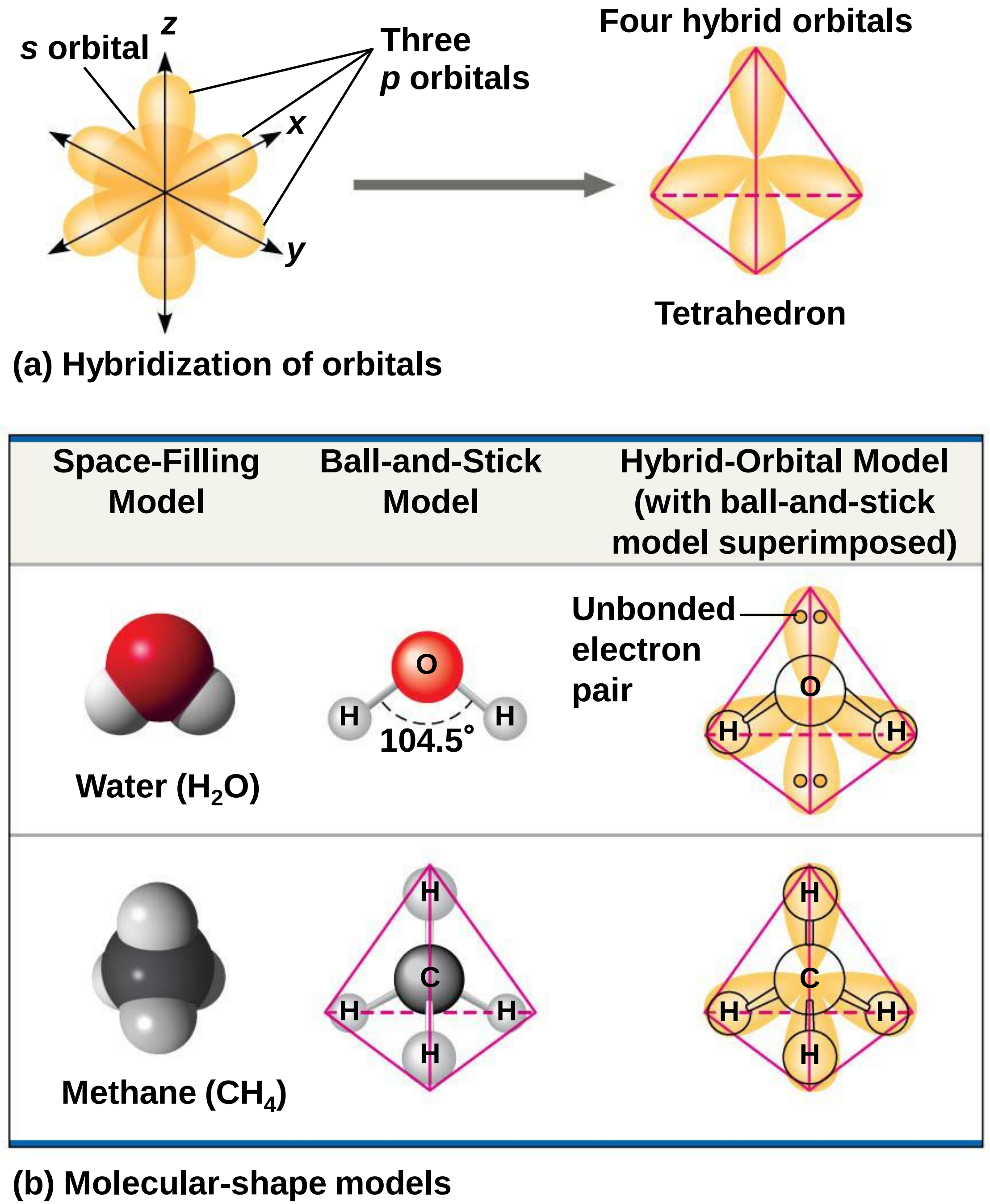
- Collectively, such interactions can be strong, as between molecules of a gecko’s toe hairs and a wall surface

Figure 2.UN02

Molecular Shape and Function

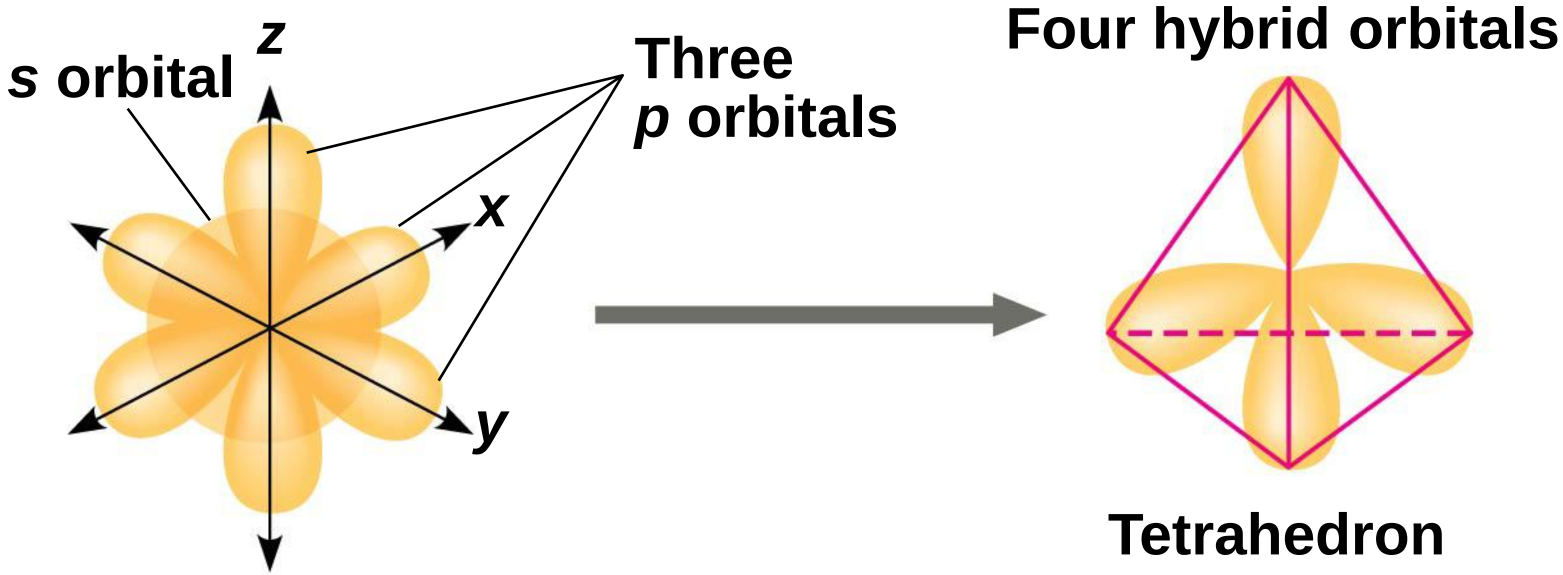
- A molecule's shape is usually very important to its function
- A molecule's shape is determined by the positions of its atoms' orbitals
- In a covalent bond, the *s* and *p* orbitals may hybridize, creating specific molecular shapes

Figure 2.15



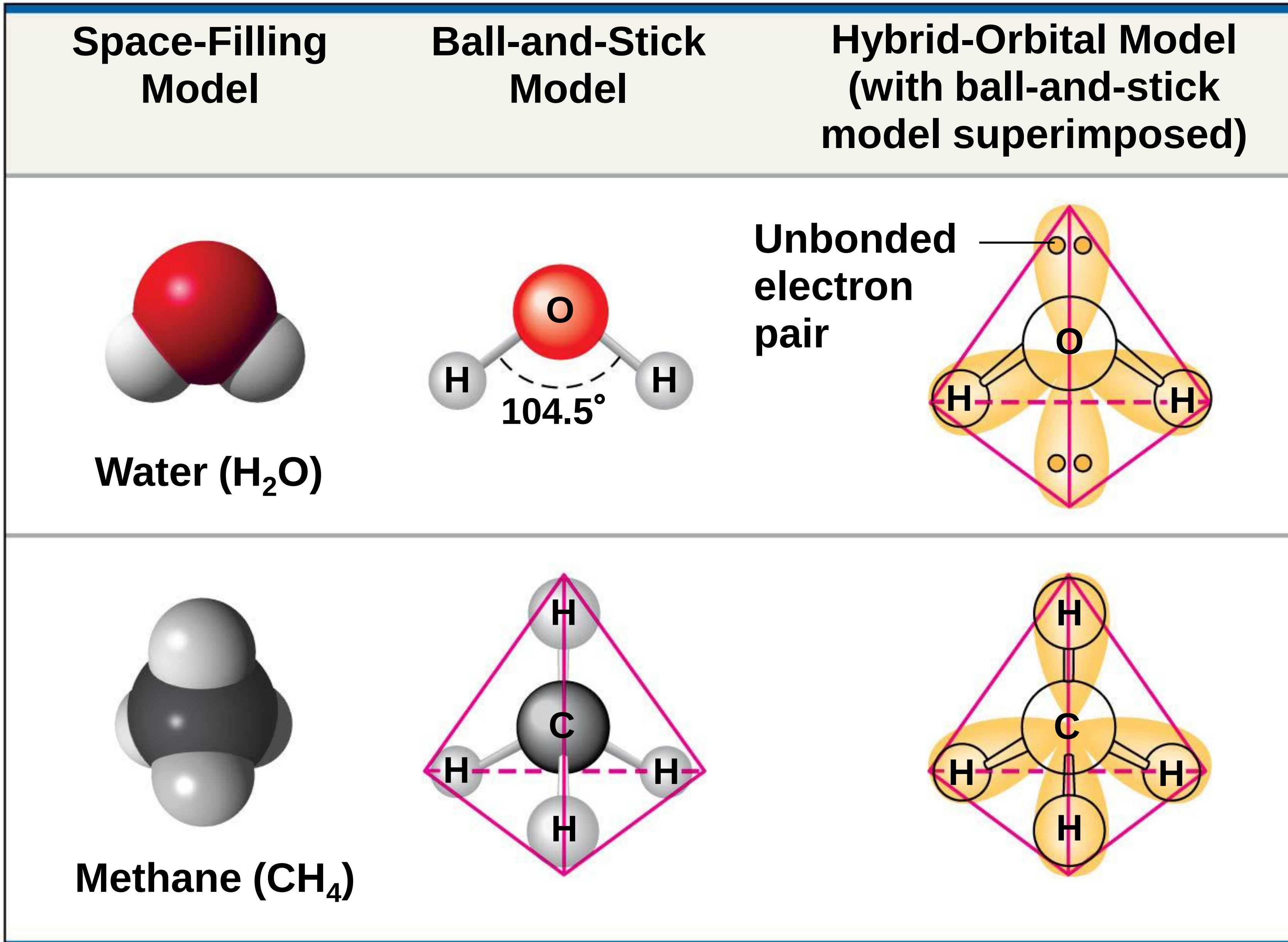
s orbital
z
x
y
Three
p orbitals
Four hybrid orbitals
Tetrahedron
(a) Hybridization of orbitals
Space-Filling Model
Ball-and-Stick Model
Hybrid-Orbital Model (with ball-and-stick model superimposed)
O
H
H
104.5°
Unbonded electron pair
Water (H_2O)
C
Methane (CH_4)
(b) Molecular-shape models

Figure 2.15a



(a) Hybridization of orbitals

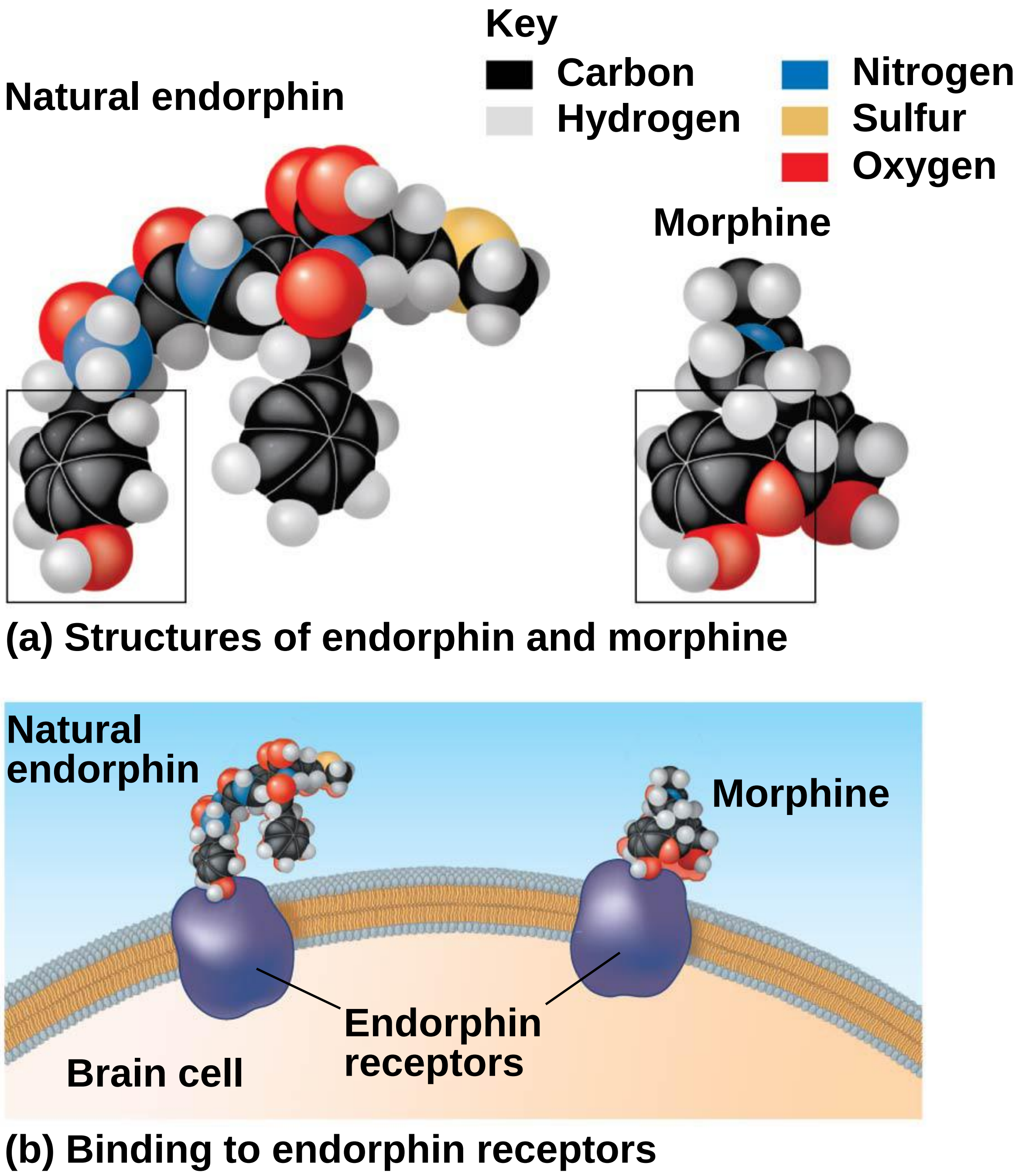
Figure 2.15b



(b) Molecular-shape models

- Molecular shape is crucial in biology because it determines how biological molecules specifically recognize and respond to one another
- Opiates, such as morphine, and naturally produced endorphins have similar effects because their shapes are similar and they bind the same receptors in the brain

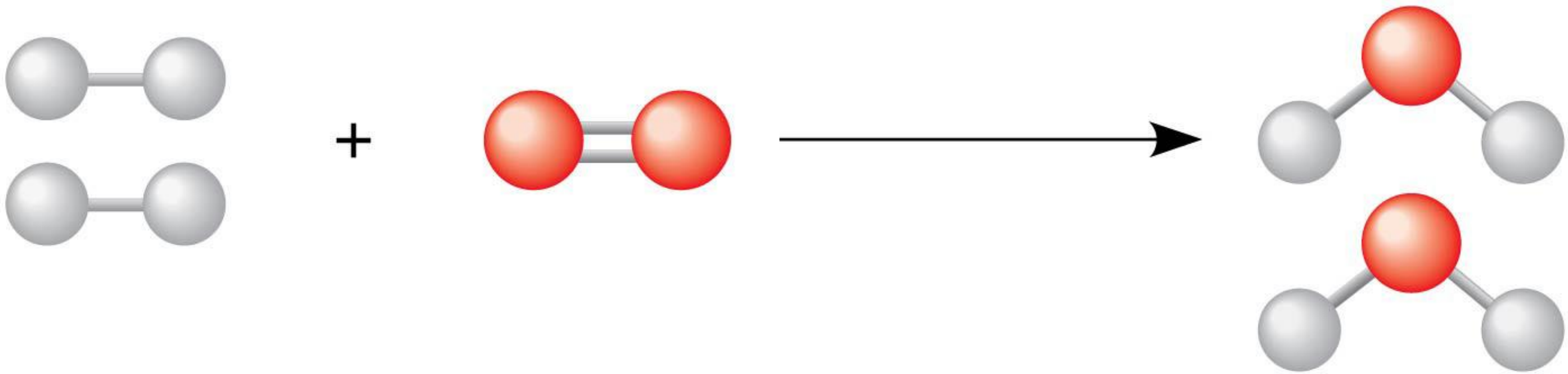
Figure 2.16


Key
Carbon
Hydrogen
Nitrogen
Sulfur
Oxygen
Natural endorphin
Morphine
(a) Structures of endorphin and morphine
Natural
endorphin
Morphine
Endorphin
receptors
Brain cell
(b) Binding to endorphin receptors

Concept 2.4: Chemical reactions make and break chemical bonds

- **Chemical reactions** are the making and breaking of chemical bonds
- The starting molecules of a chemical reaction are called **reactants**
- The final molecules of a chemical reaction are called **products**

Figure 2.UN03



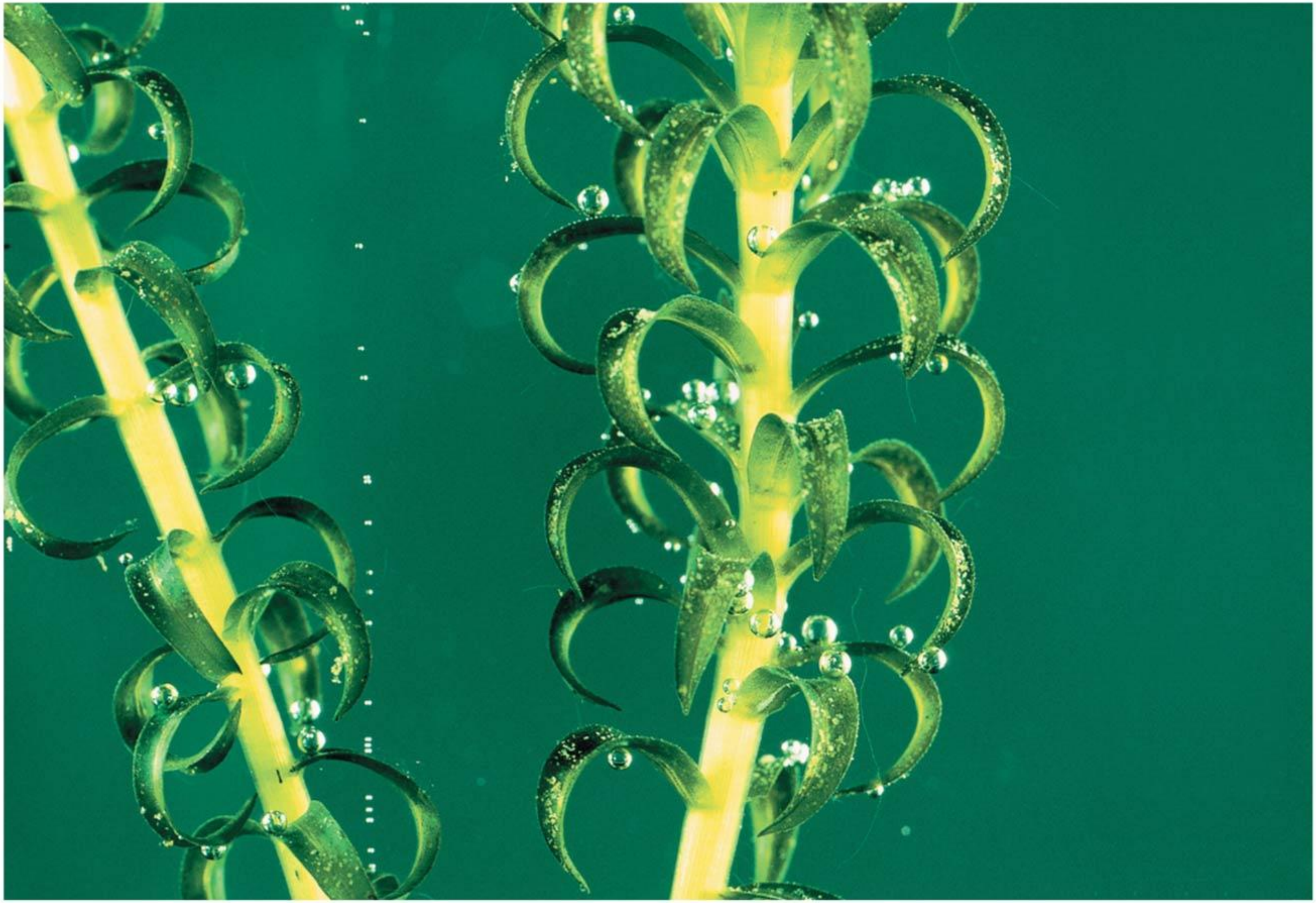
$$2\,H_2 + O_2 \longrightarrow 2\,H_2O$$

Reactants **Reaction** **Products**

- Photosynthesis is an important chemical reaction
- Sunlight powers the conversion of carbon dioxide and water to glucose and oxygen

$$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$$

Figure 2.17



- All chemical reactions are reversible: products of the forward reaction become reactants for the reverse reaction
- **Chemical equilibrium** is reached when the forward and reverse reactions occur at the same rate
- At equilibrium the relative concentrations of reactants and products do not change

Figure 2.UN01a

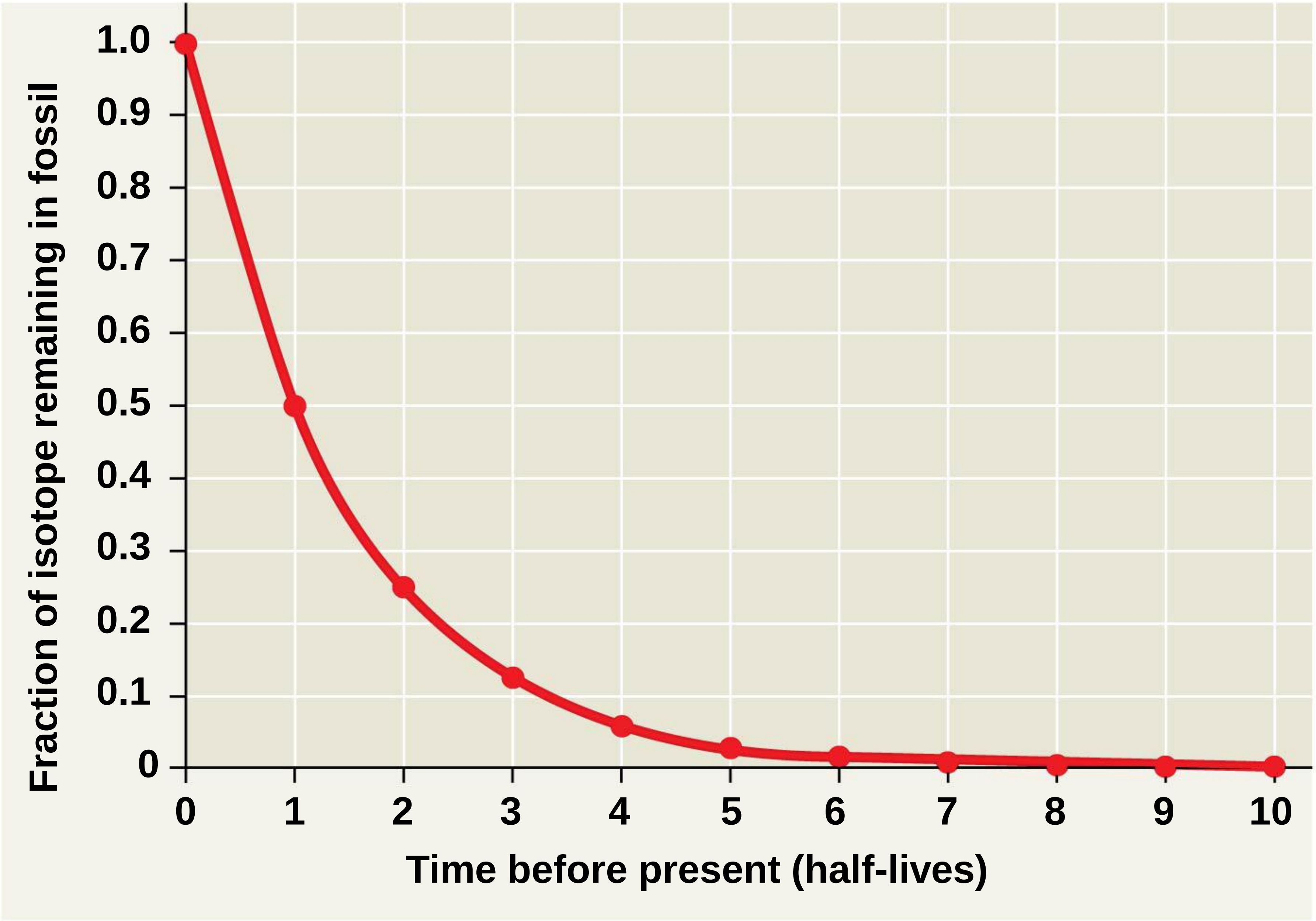


Figure 2.UN01b

Neanderthal fossils

Figure 2.UN04

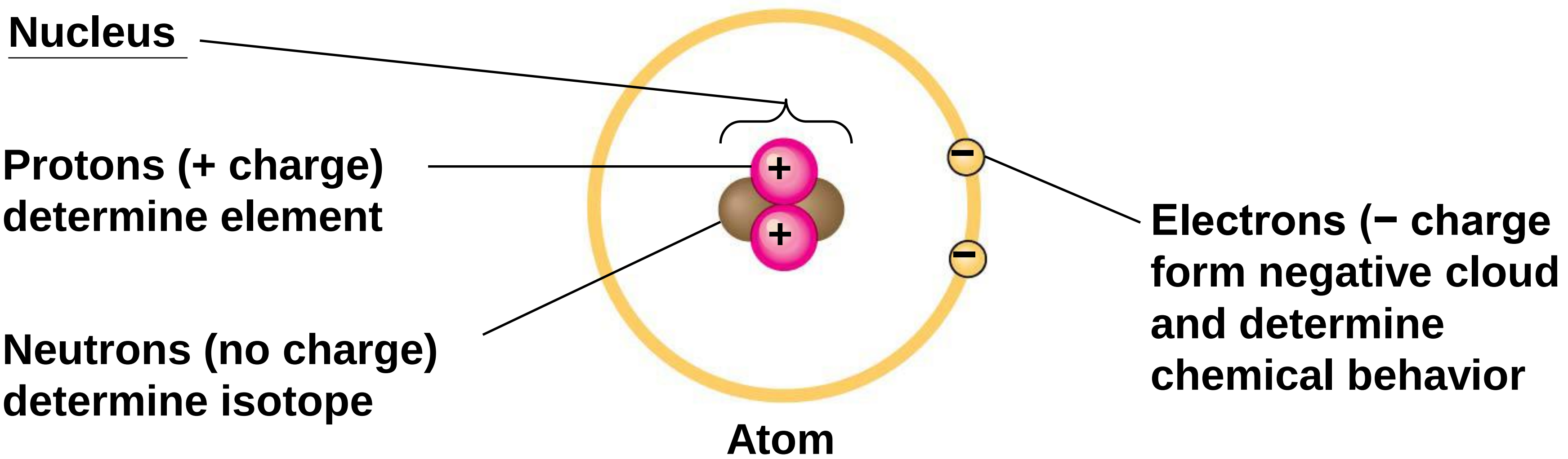


Figure 2.UN05

Figure 2.UN06

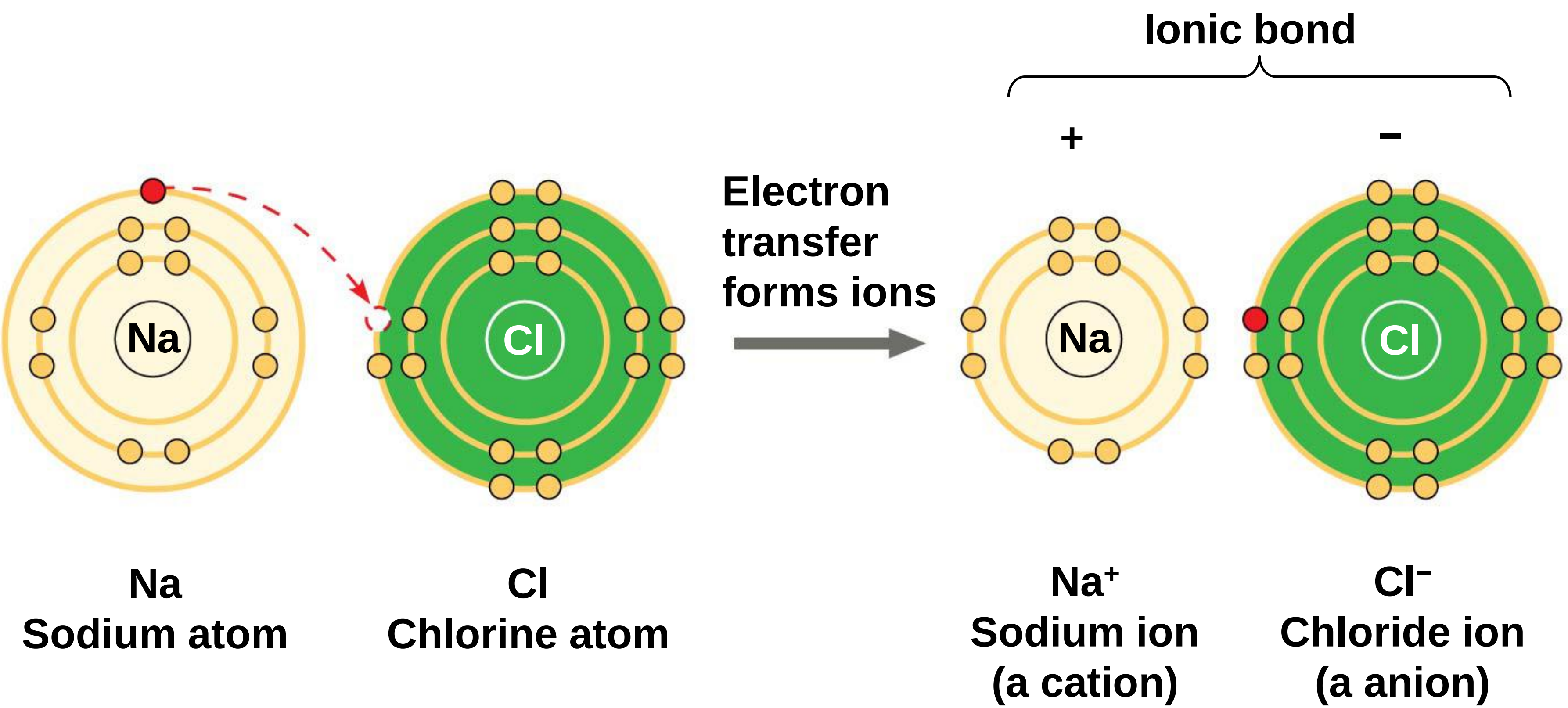


Figure 2.UN07

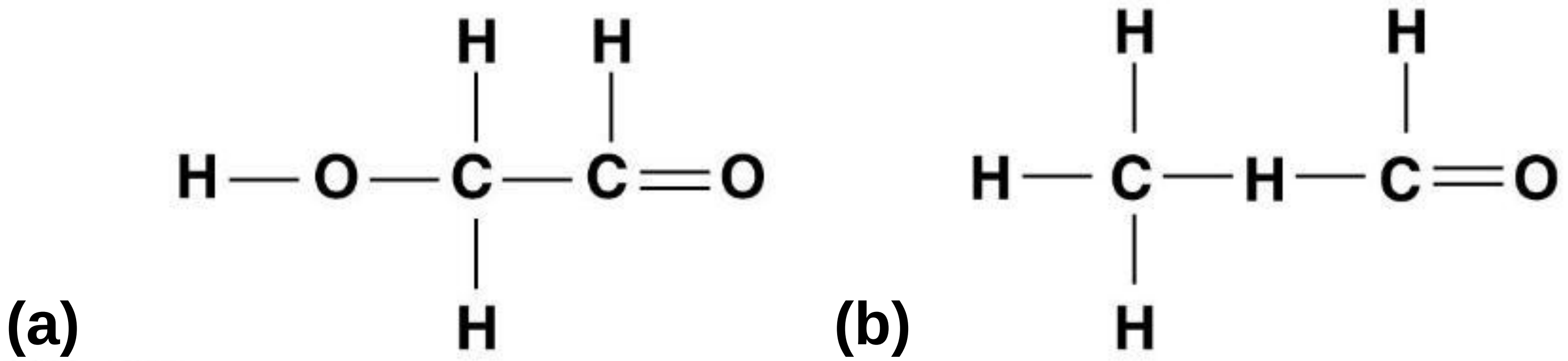


Figure 2.UN08

Figure 2.UN09