Water
Carbon
Life

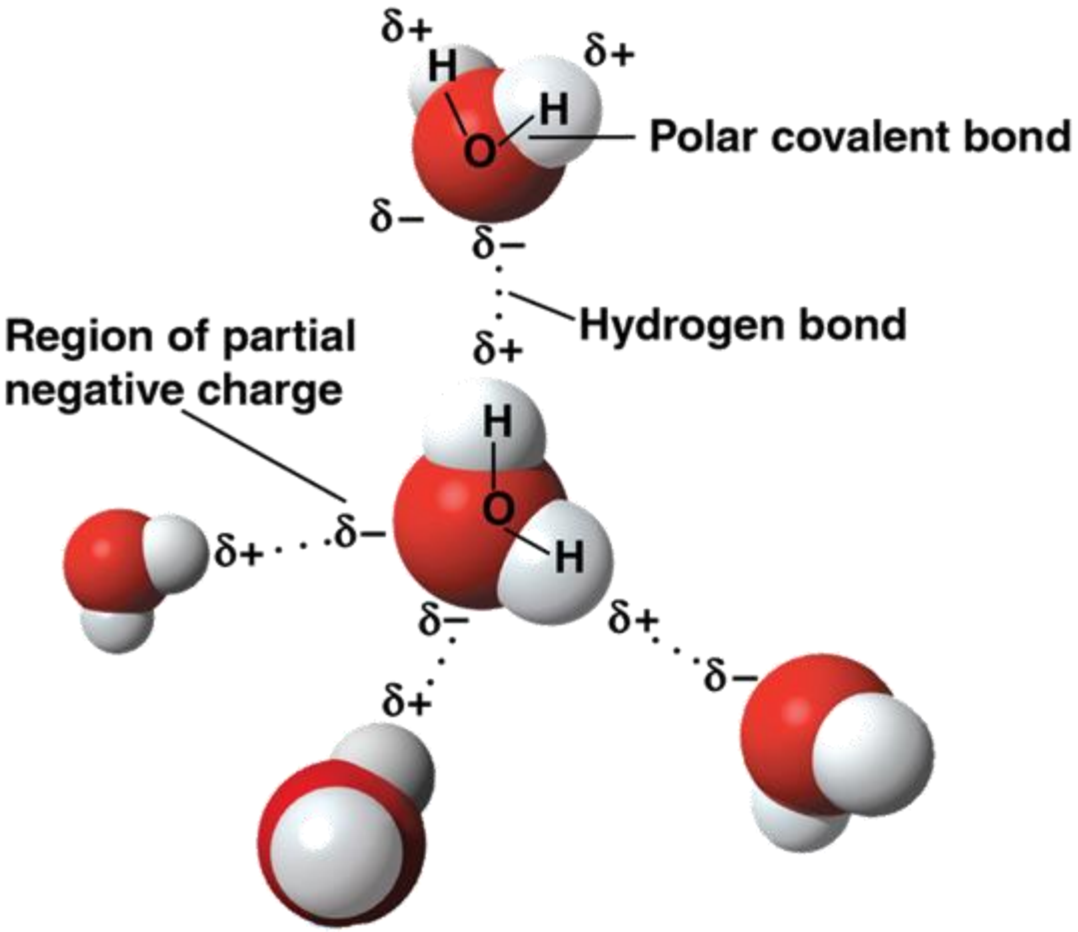
Water

The Molecule That Supports All of Life

- Water makes life possible on Earth
- Water is the only common substance to exist in the natural environment in all three physical states of matter
- Water's unique emergent properties help make Earth suitable for life
- The structure of the water molecule allows it to interact with other molecules

Structure of water: Why does ice float on liquid water?

- Electrons of the **polar covalent bonds** in water spend more time near the **O**xygen than the **H**ydrogen
- Water molecules are **polar -** the overall charge is unevenly distributed in the molecule
- Polarity allows water molecules to form hydrogen bonds with each other



Structure of water: Why does ice float on liquid water?

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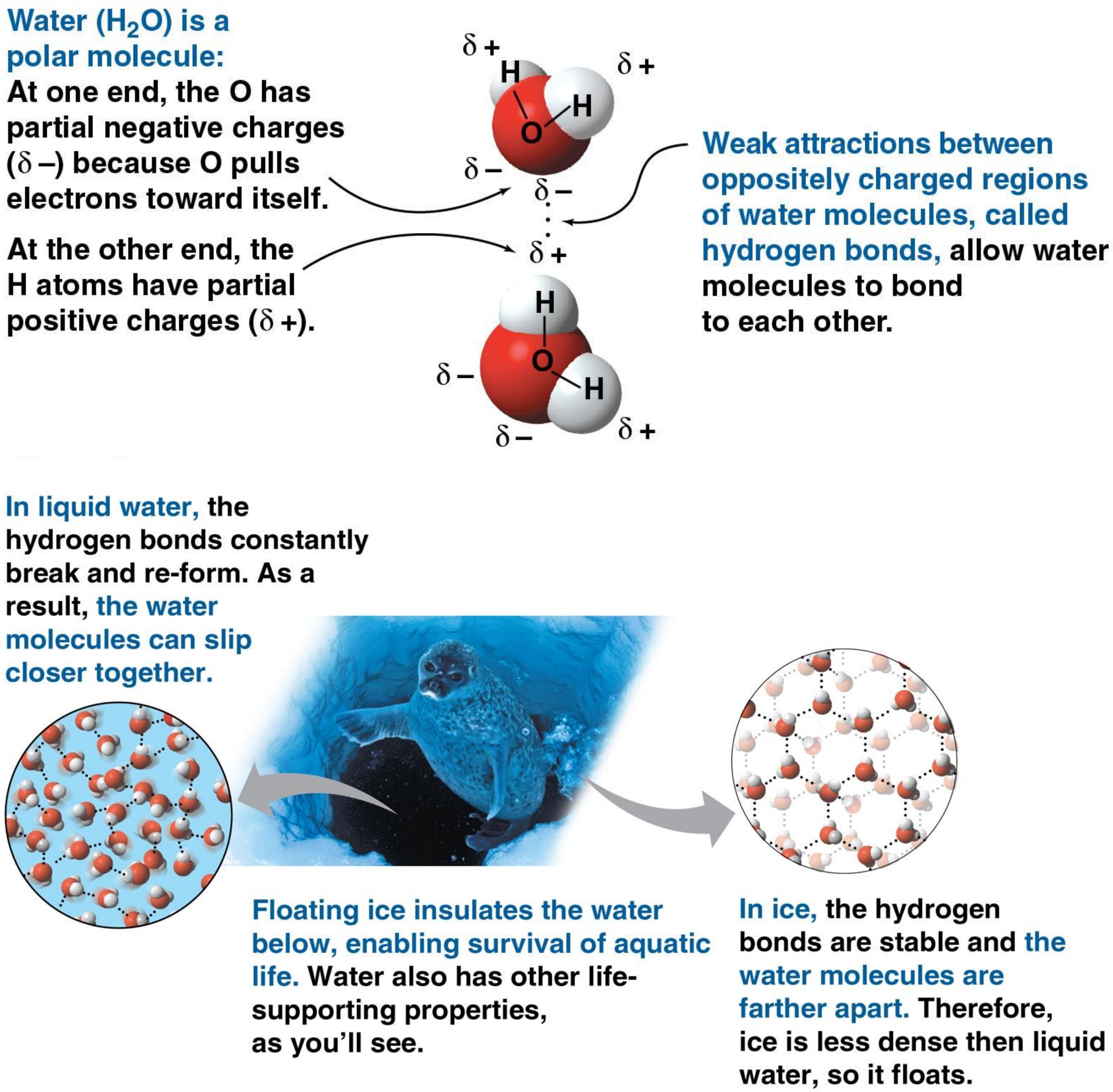


Emergent properties of water facilitate life on Earth

Cohesive behavior

Ability to moderate temperature

Expansion upon freezing

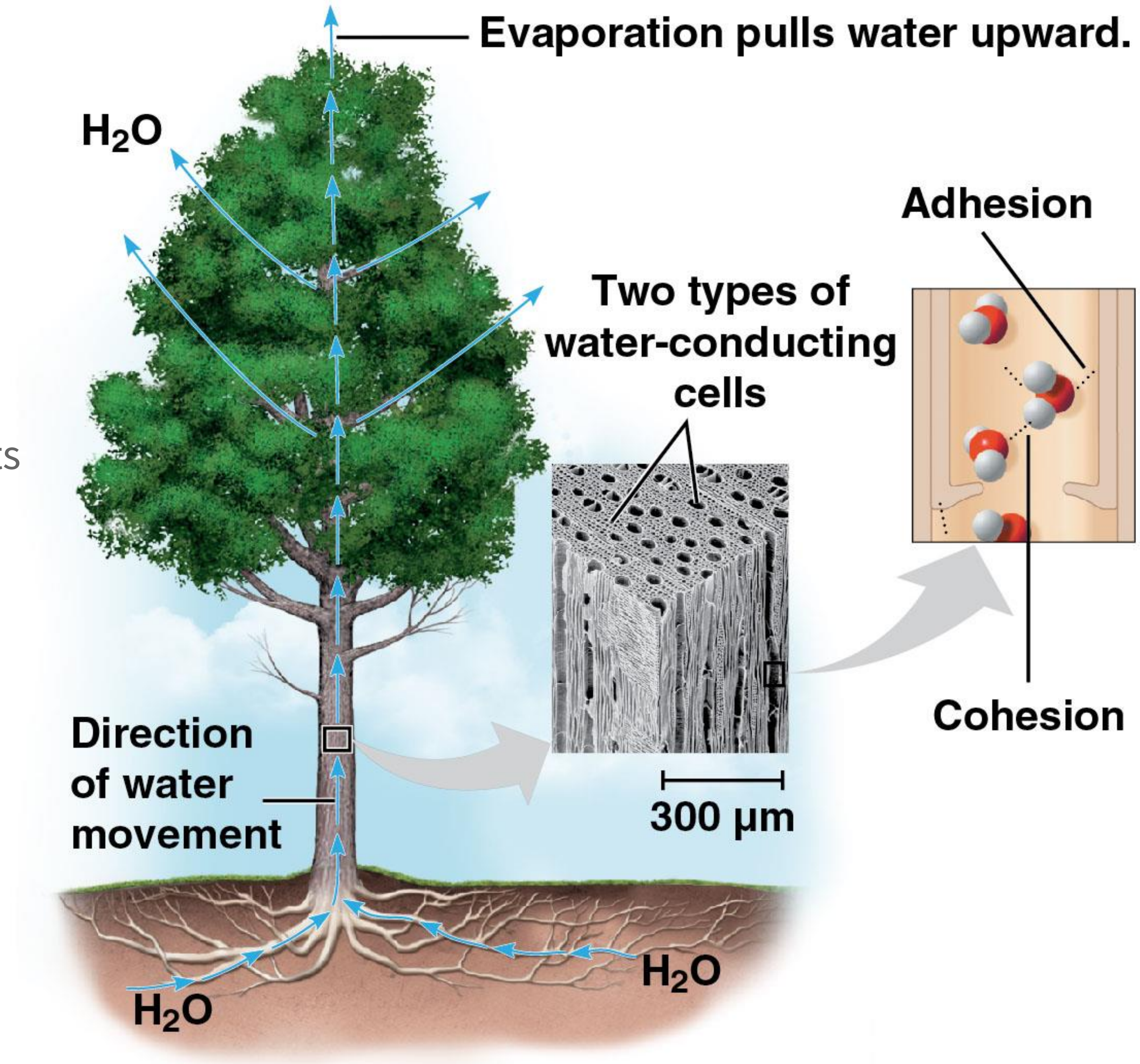
Versatility as a solvent

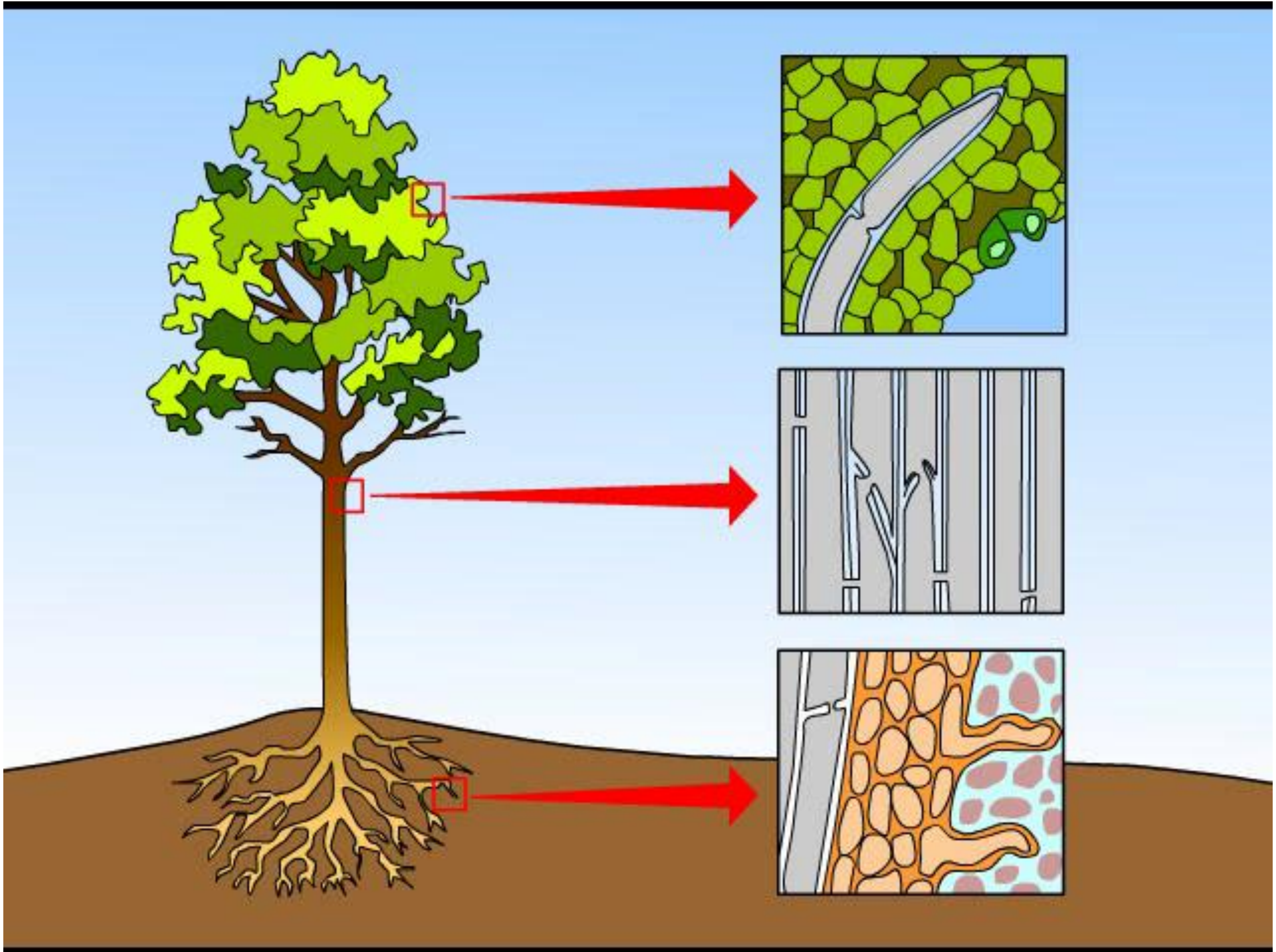
Cohesion of Water Molecules

- Hydrogen bonds hold water molecules together, this phenomenon called **cohesion**
- Cohesion results in high **surface tension**, a measure of how difficult it is to break the surface of a liquid
- Water has an unusually high surface tension due to hydrogen bonding between the molecules at the air-water interface and to the water below

Cohesion of Water Molecules

- Cohesion contributes to the transport of water and dissolved nutrients against gravity in plants
- **Adhesion** is an attraction between different substances. Eg. between water and plant cell walls
- This helps to counter the downward pull of gravity





Moderation of Temperature by Water 🌡

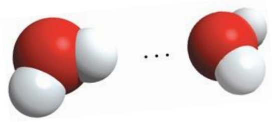
- Water moderates air temperature
  - absorbs heat from warmer air and releases stored heat to cooler air
- Water as a heat bank
  - absorbs or releases large amount of heat with only a slight change in its own temperature

Moderation of Temperature by Water

- The kinetic energy from random motion of molecules is called **thermal energy**
- **Temperature** represents the average kinetic energy of the molecules in matter
- Thermal energy in transfer from one matter to another is defined as **heat**

Water’s High Specific Heat

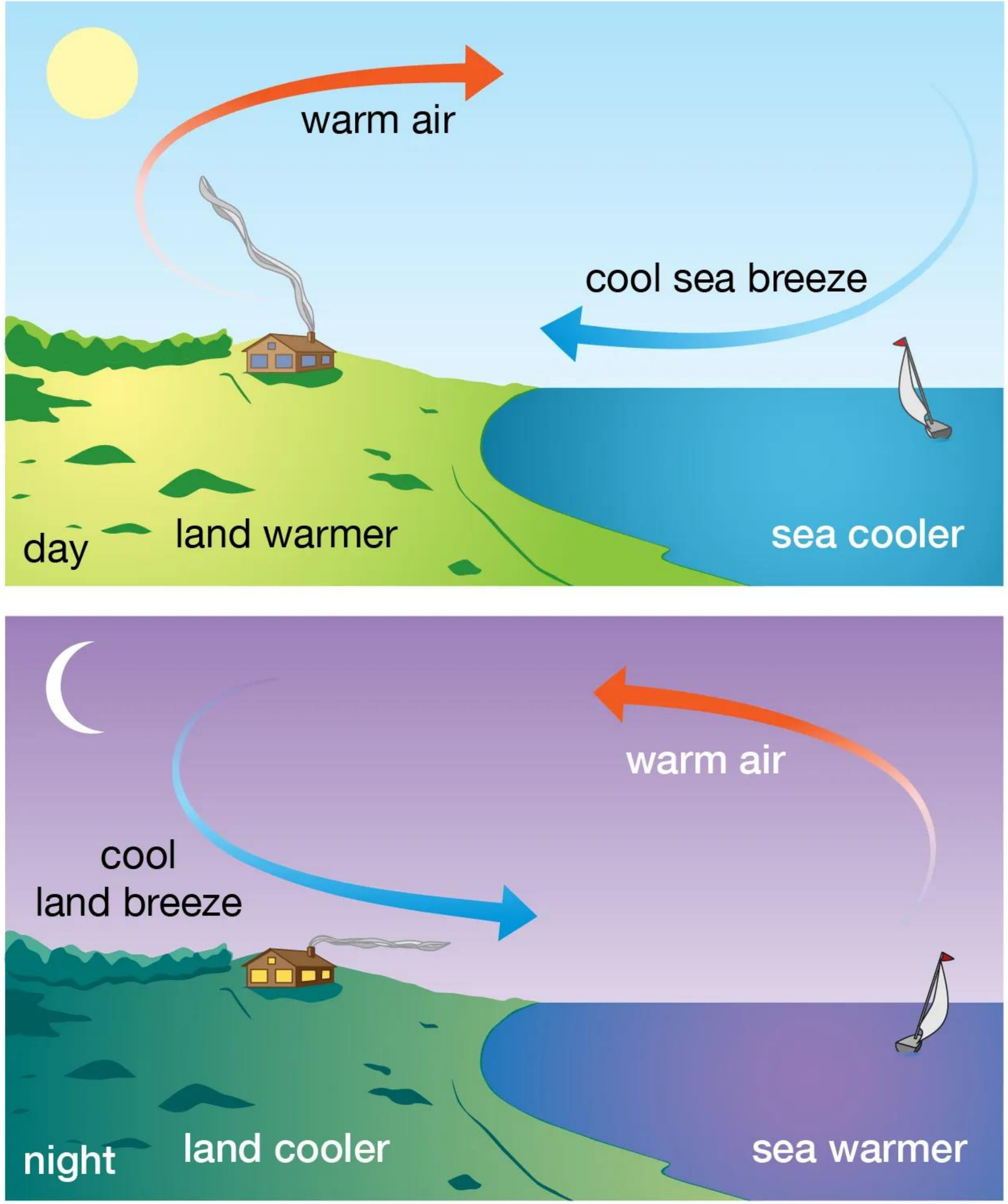
- The **specific heat** of a substance is the amount of heat that must be absorbed or lost for 1 g of that substance to change its temperature by 1°C
- The specific heat of water is 1 cal/(g • °C)
- Water resists changing its temperature because of its high specific heat
- Water’s high specific heat can be traced to hydrogen bonding
  - Heat is absorbed when hydrogen bonds break
  - Heat is released when hydrogen bonds form



- The high specific heat of water minimizes temperature fluctuations to within limits that permit life

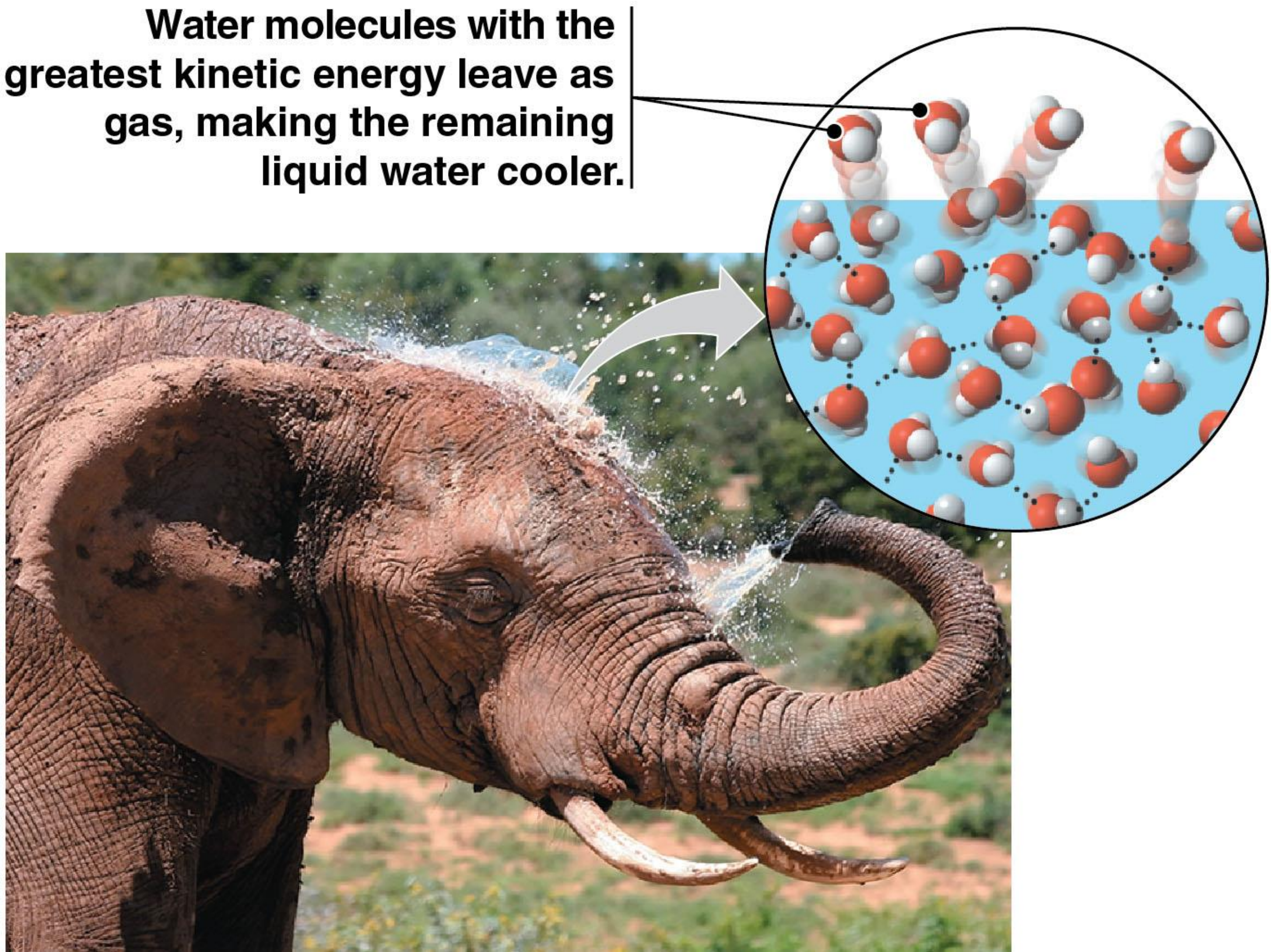
Moderation of Temperature by Water

- A large body of water can absorb and store a huge amount of heat from the sun in daytime and during summer while warming up only a few degrees
- At night and during the winter the gradually cooling water can warm the air
- This serves to moderate air temperature in coastal areas



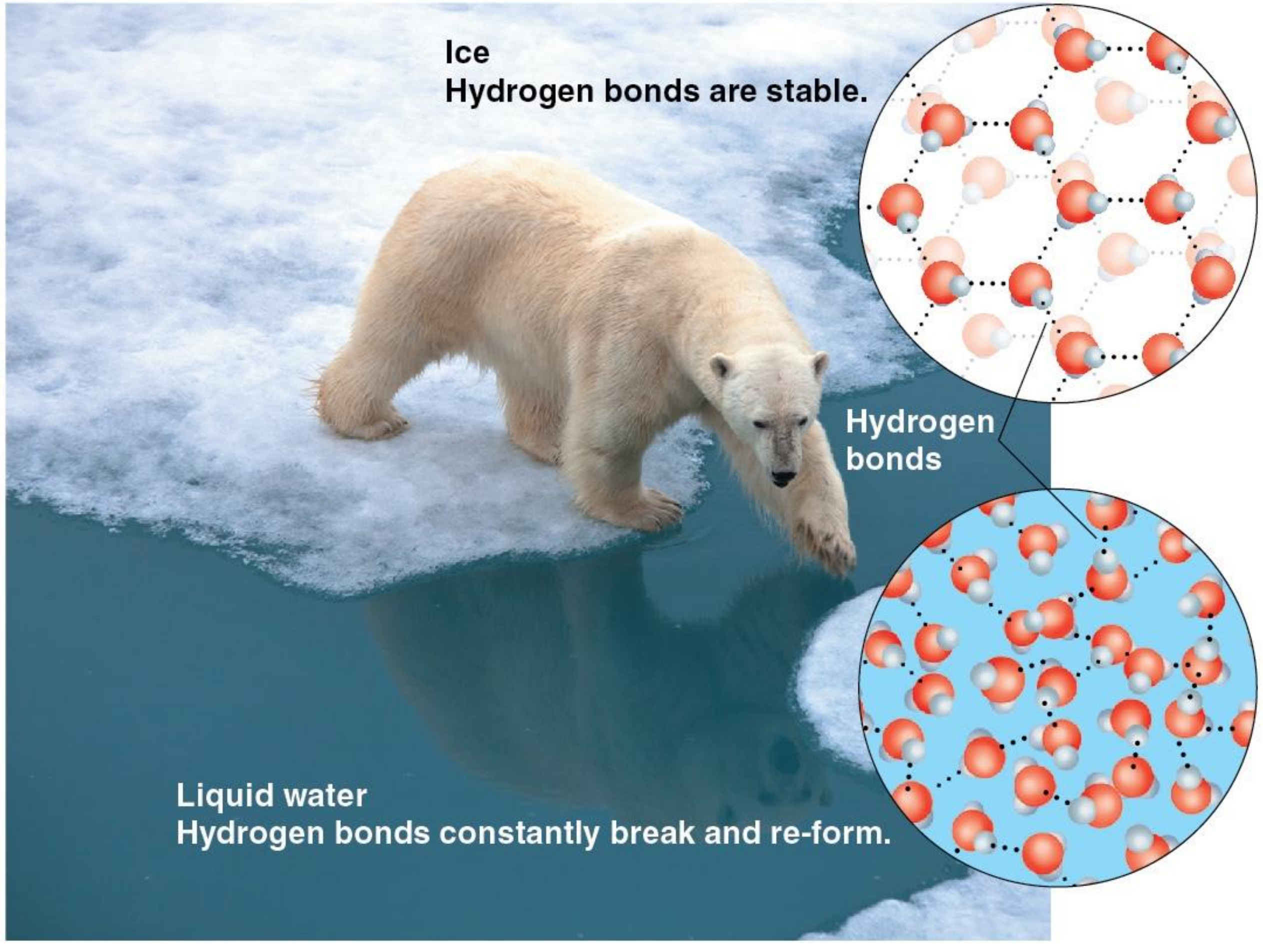
Evaporative Cooling

- Evaporation (vaporization) is transformation of a substance from liquid to gas
- **Heat of vaporization** is the heat a liquid must absorb for 1 g to be converted to gas
- As a liquid evaporates, its remaining surface cools, through a process called **evaporative cooling**
- Evaporative cooling of water helps stabilize temperatures in organisms and bodies of water



Expansion upon freezing

- H_2O at 4°C - highest density
- H_2O at 0°C - molecules are locked into a crystalline lattice
- The hydrogen bonds keep the molecules far enough apart to make the ice ~10% less dense than liquid water

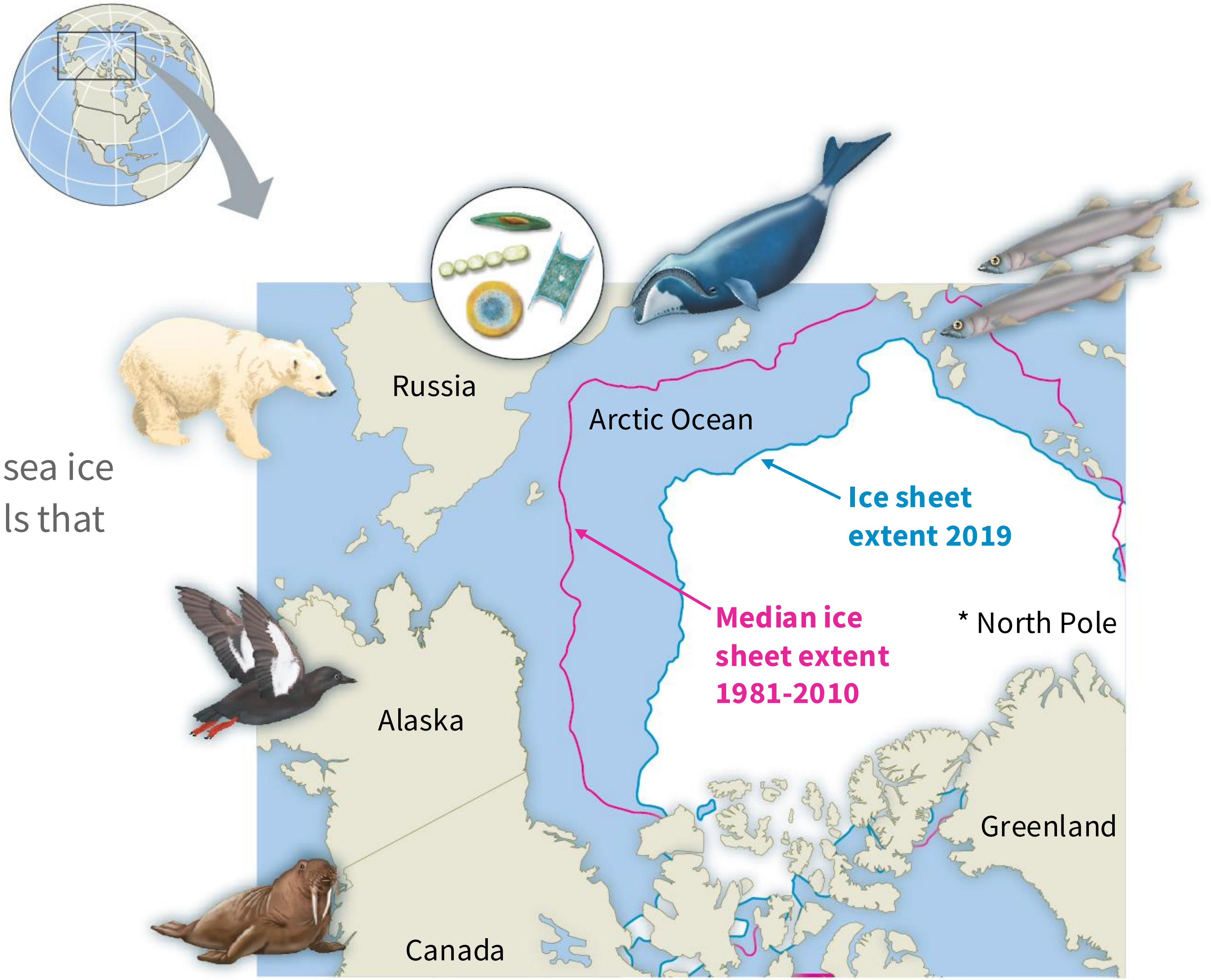


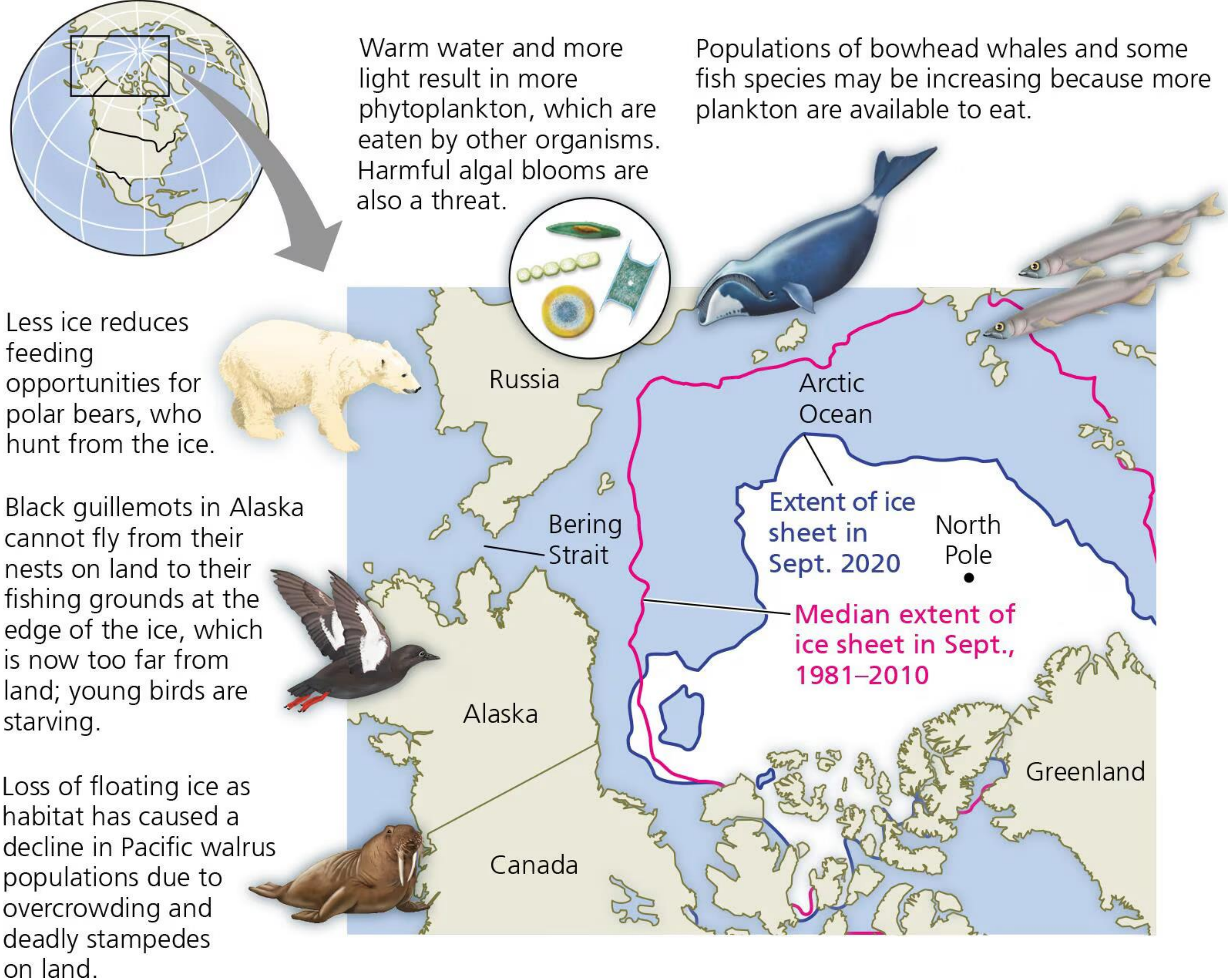
- Ice floats in liquid water because hydrogen bonds in ice are more “ordered”
- Ice insulates the water bellow
- If ice sank, all bodies of water would eventually freeze solid, making life impossible on Earth

Cryosphere

- Global warming effects cryosphere environments
- Disappearance of glaciers and Arctic sea ice poses an extreme challenge to animals that depend on ice for survival

Cryosphere:
krios – cold
sphere – globe

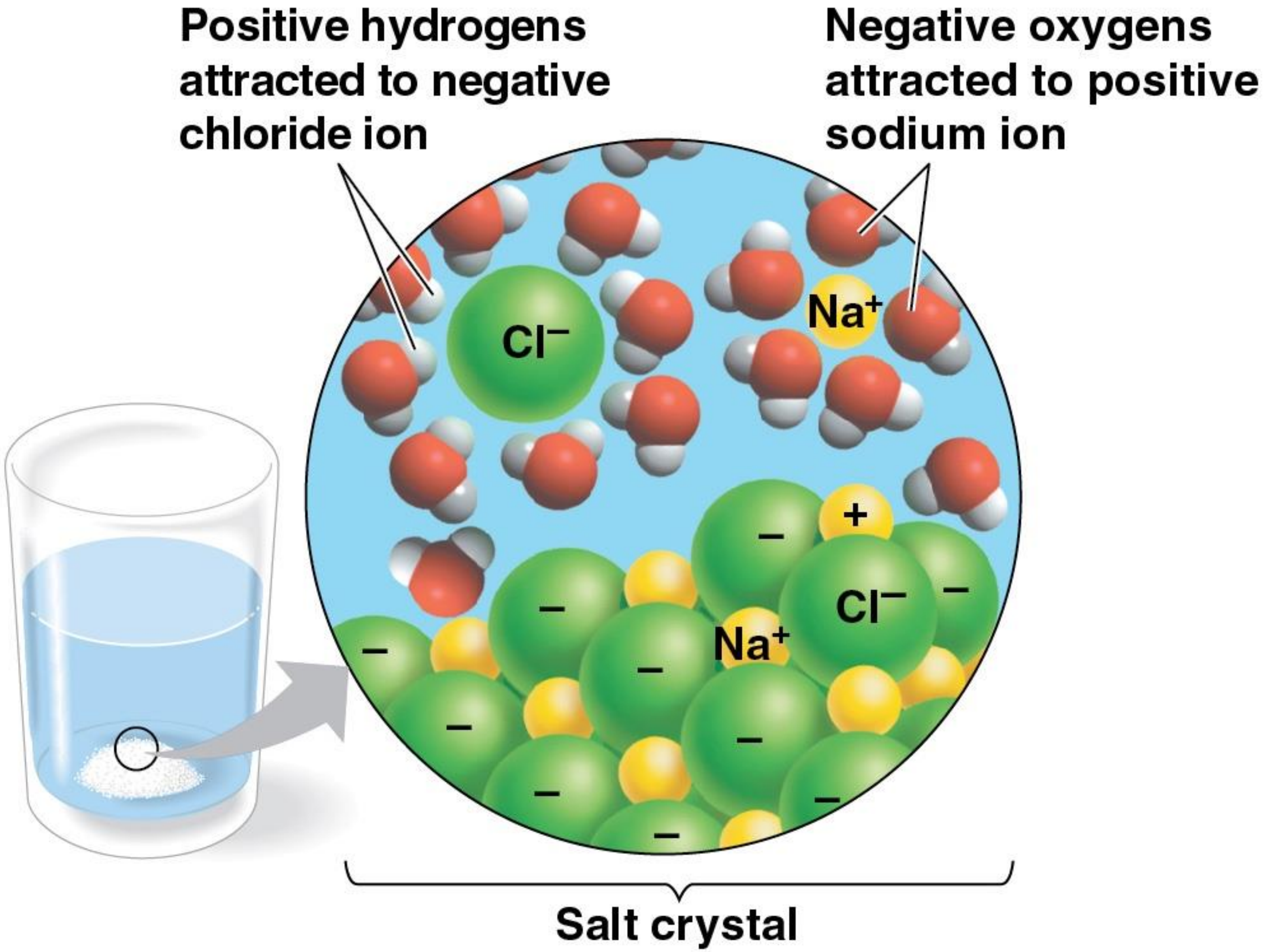




Warm water and more light result in more phytoplankton, which are eaten by other organisms. Harmful algal blooms are also a threat.
Populations of bowhead whales and some fish species may be increasing because more plankton are available to eat.
Less ice reduces feeding opportunities for polar bears, who hunt from the ice.
Black guillemots in Alaska cannot fly from their nests on land to their fishing grounds at the edge of the ice, which is now too far from land; young birds are starving.
Loss of floating ice as habitat has caused a decline in Pacific walrus populations due to overcrowding and deadly stampedes on land.
Russia
Arctic Ocean
Bering Strait
Extent of ice sheet in Sept. 2020
North Pole
Median extent of ice sheet in Sept., 1981–2010
Alaska
Greenland
Canada

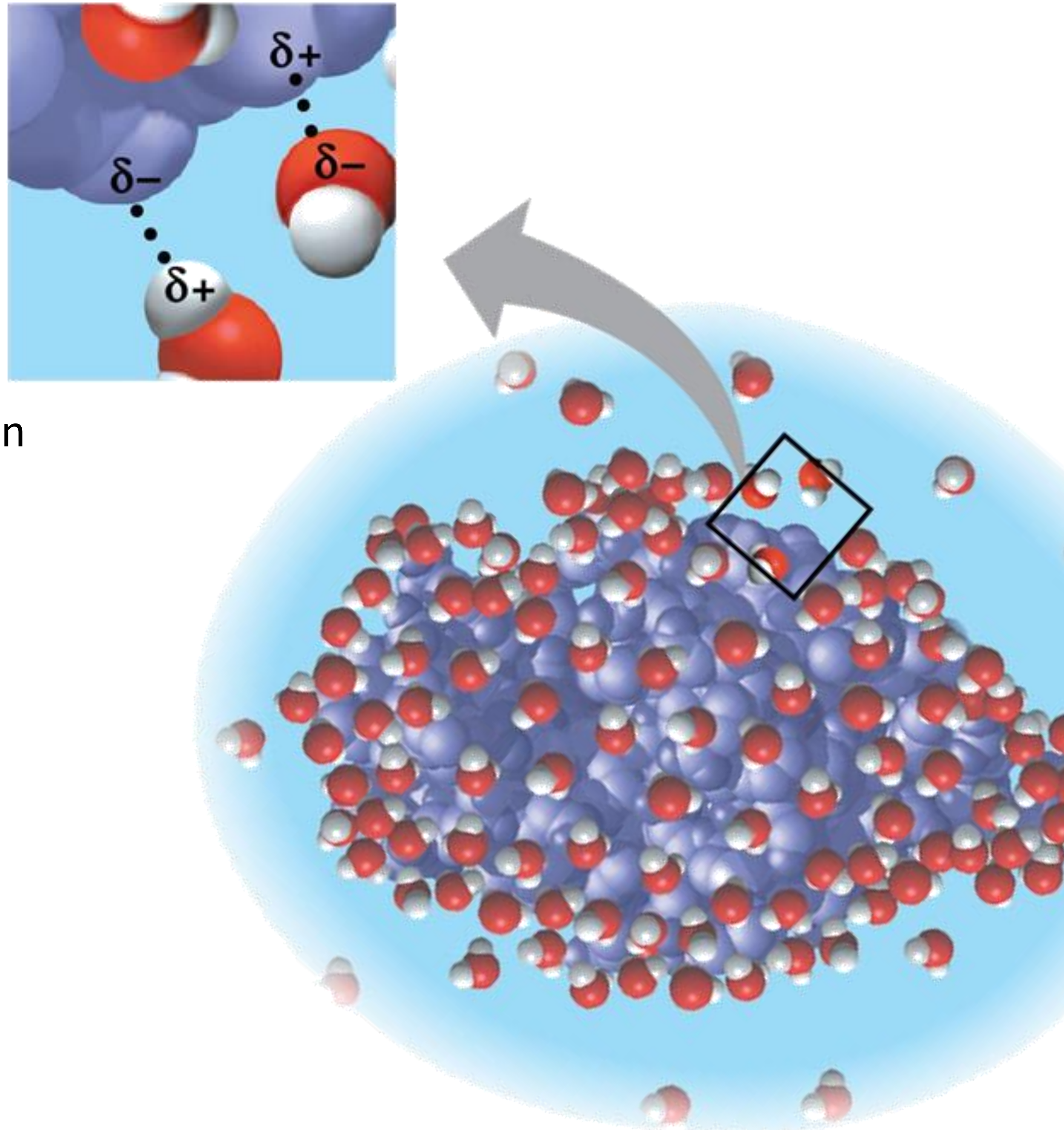
Versatility as a solvent

- A **solution** is a liquid that is a completely homogeneous mixture of substances
- The **solvent** is the dissolving agent of a solution
- The **solute** is the substance that is dissolved
- An **aqueous solution** is one in which water is the solvent



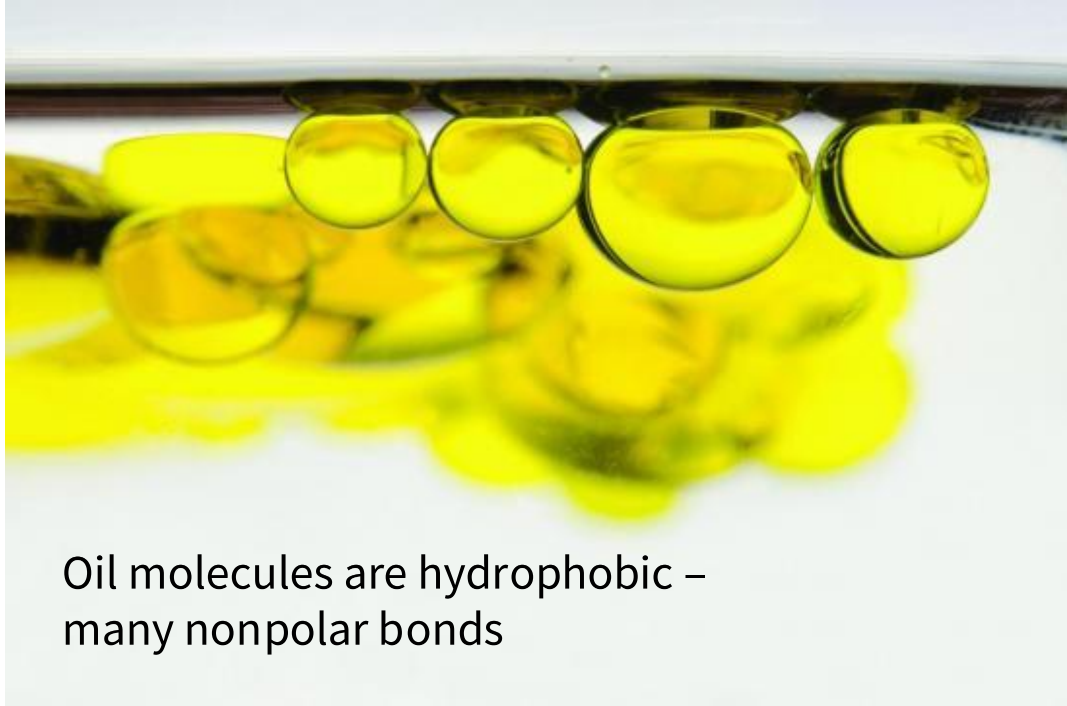
Versatility as a solvent

- Water is a versatile solvent due to its polarity
- When an ionic compound is dissolved in water, each ion is surrounded by a sphere of water molecules called a **hydration shell**
- Water can also dissolve compounds made of nonionic polar molecules
- Even large polar molecules such as proteins can dissolve in water if they have ionic and polar regions

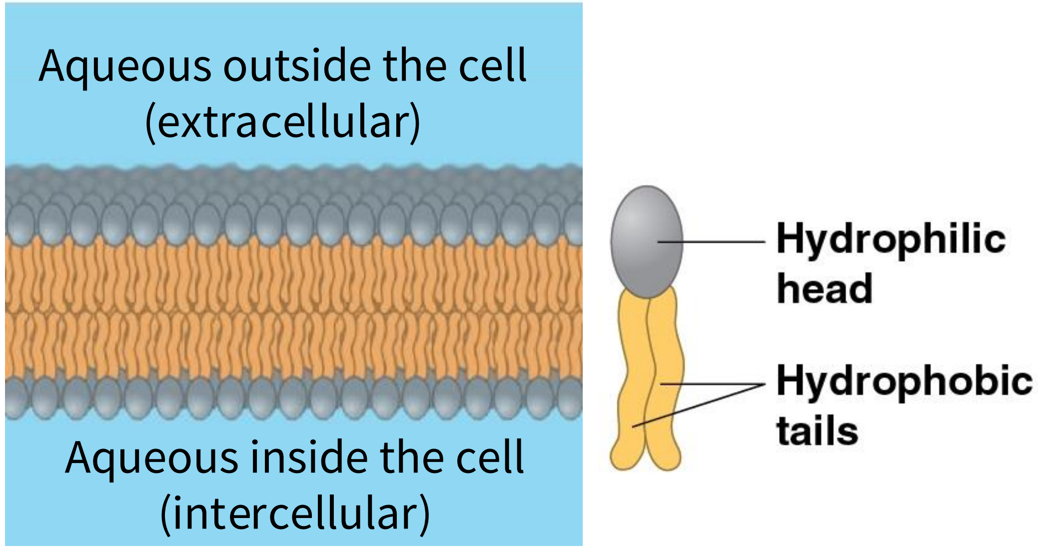


Hydrophilic and Hydrophobic Substances

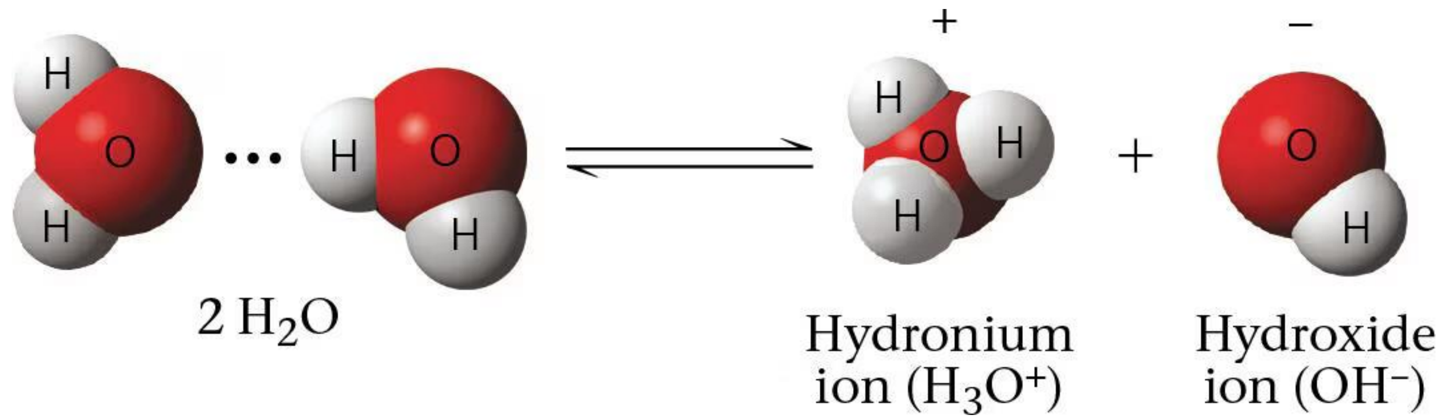
- **Hydrophilic** substances have affinity for water molecules
- **Hydrophobic** substances repel water molecules



Hydrophobic molecules are the major components of **cell membranes**

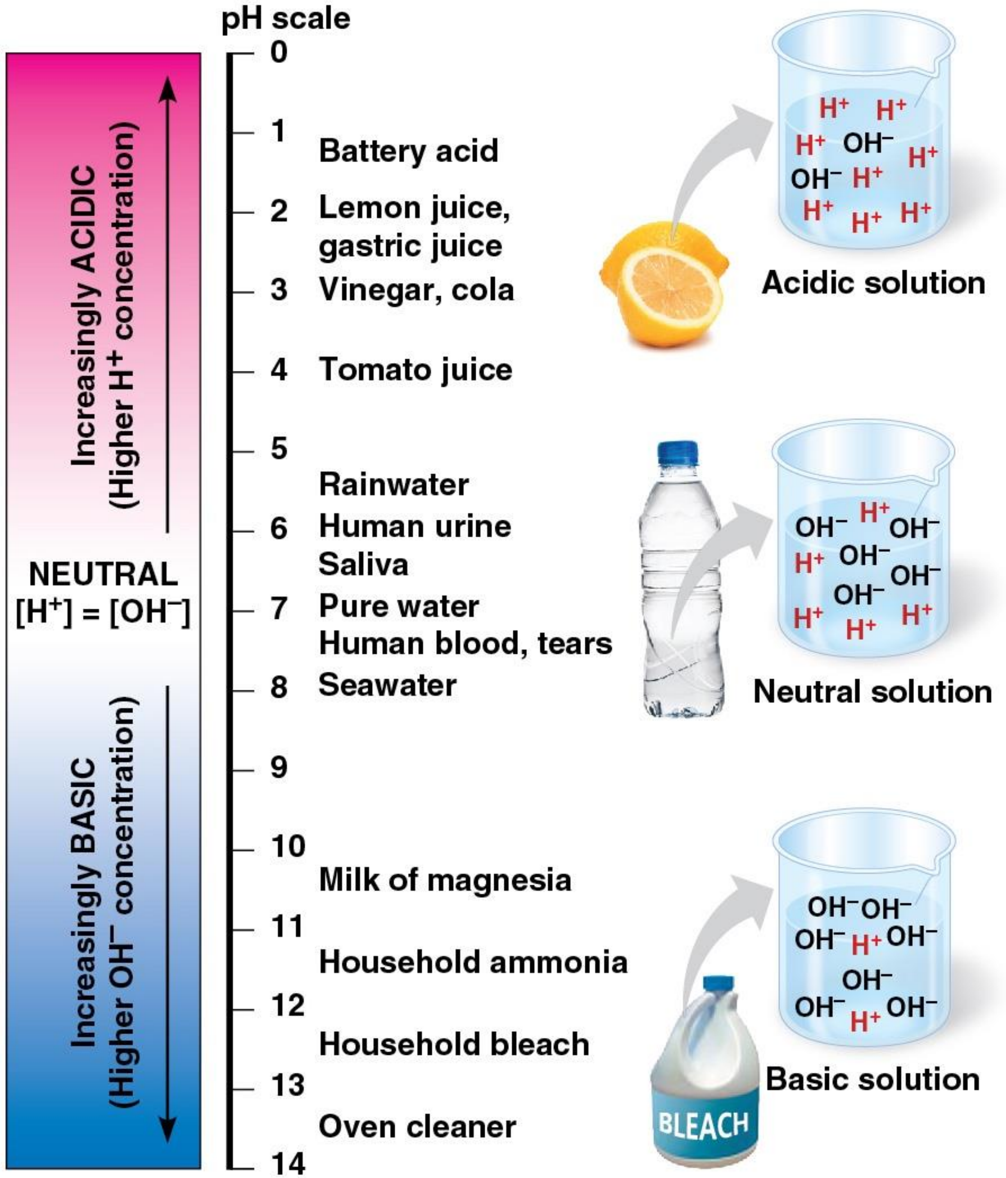


- In liquid water, a very small percentage of water molecules break apart into ions.



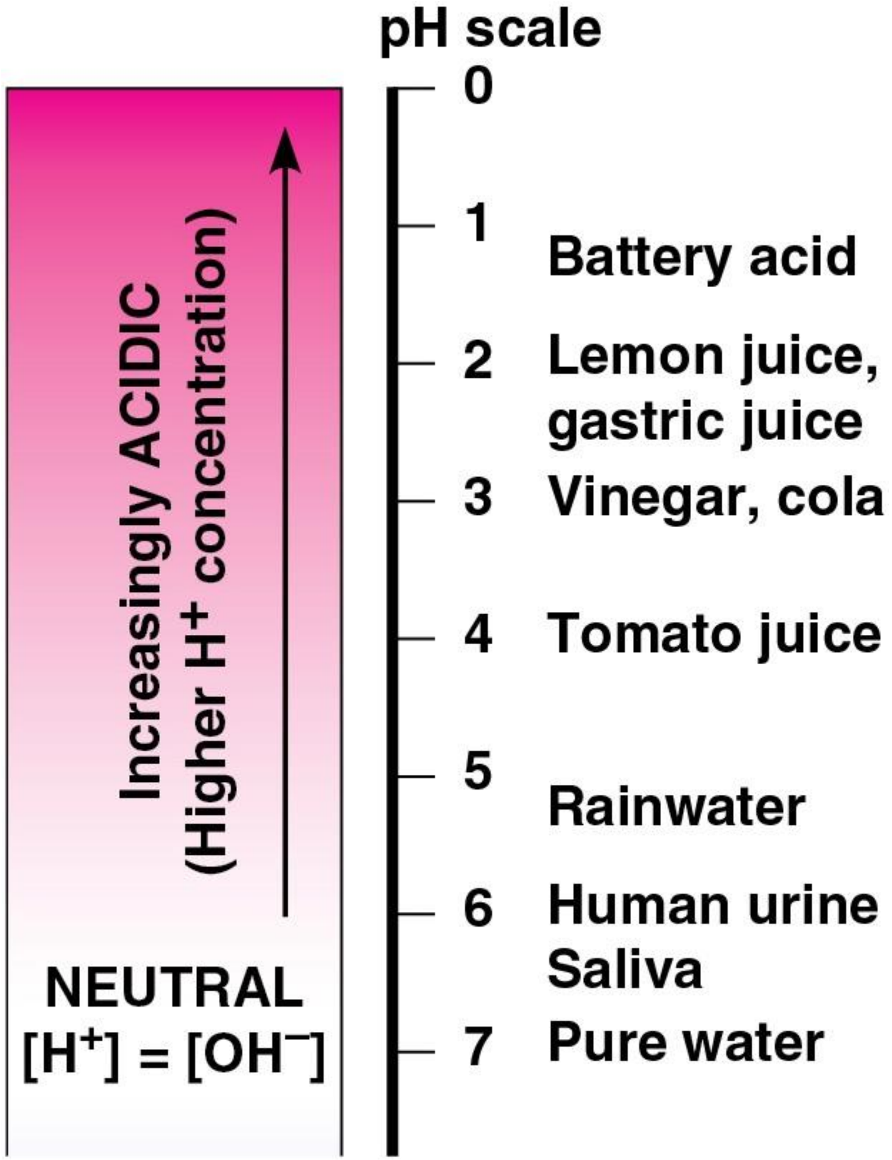
- We use the **pH scale** to describe how acidic or basic a solution is

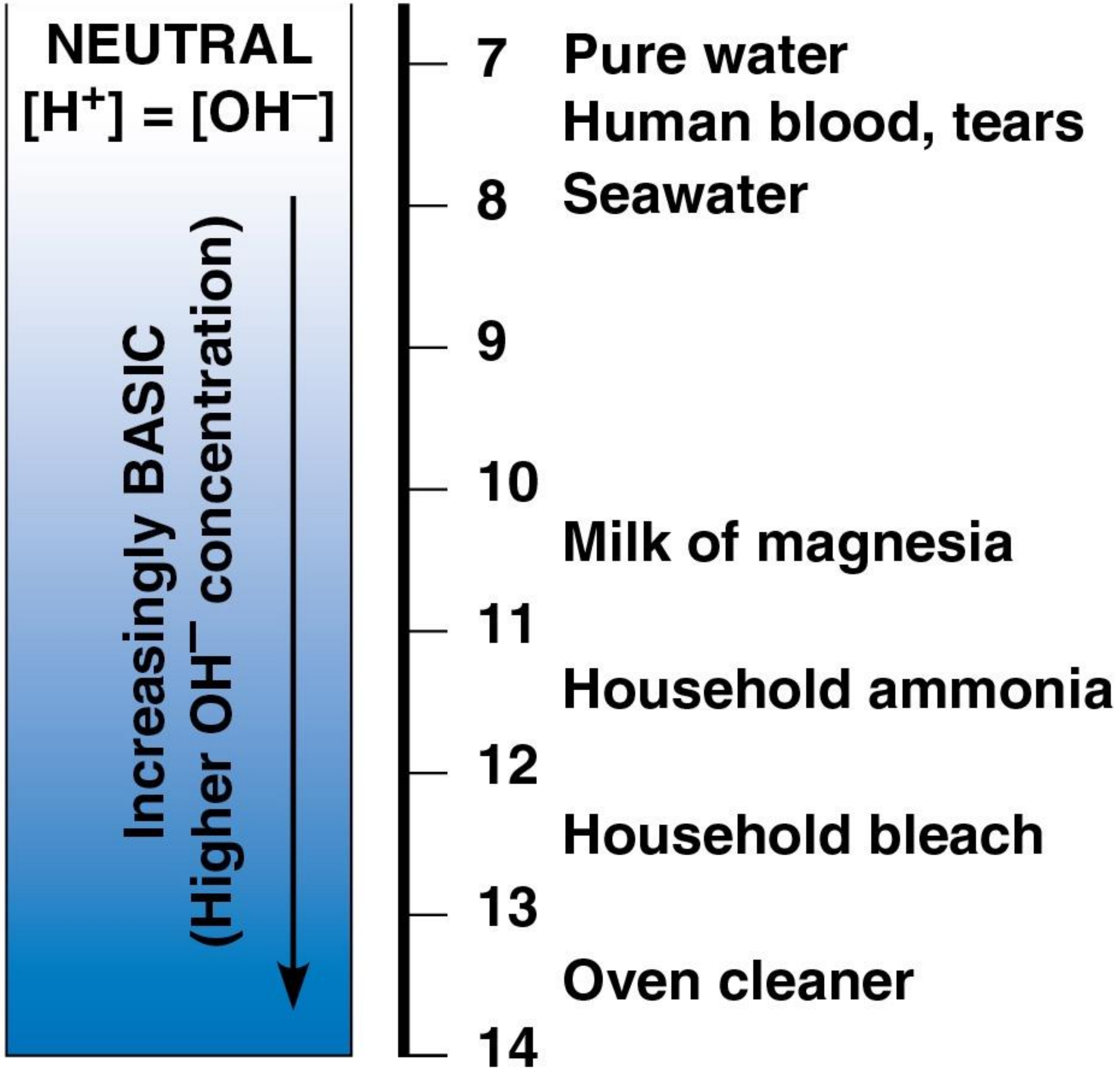
$$HCl \rightarrow H^+ + Cl^-$$

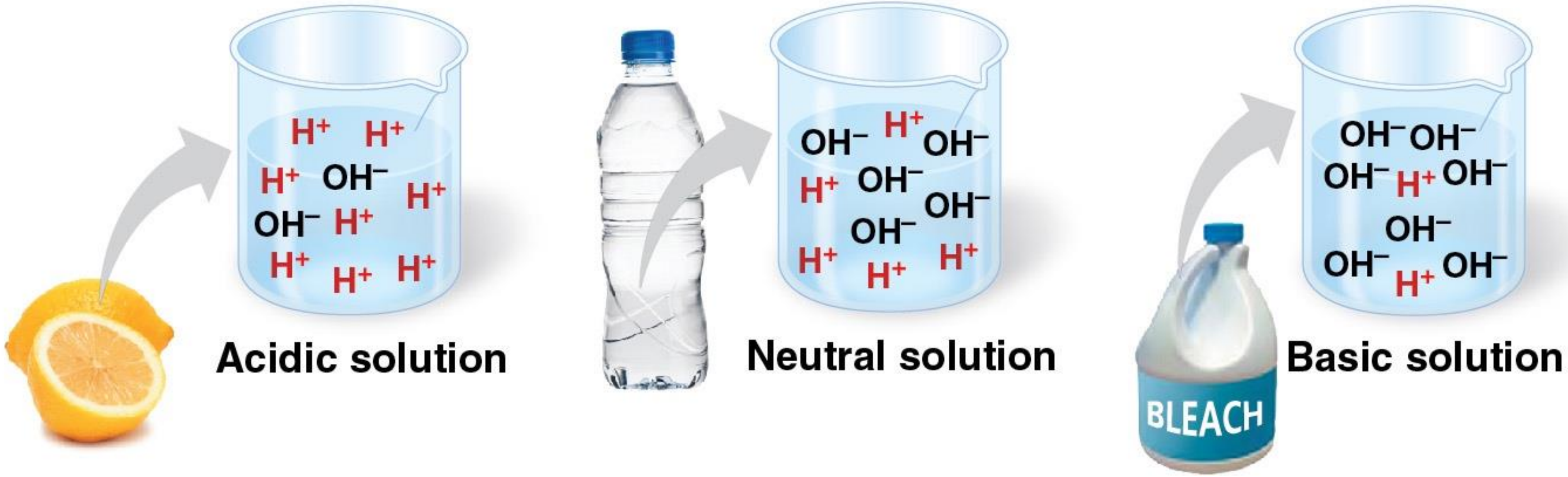


$$NH_3 + H^+ \rightleftharpoons NH_4{}^+$$

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

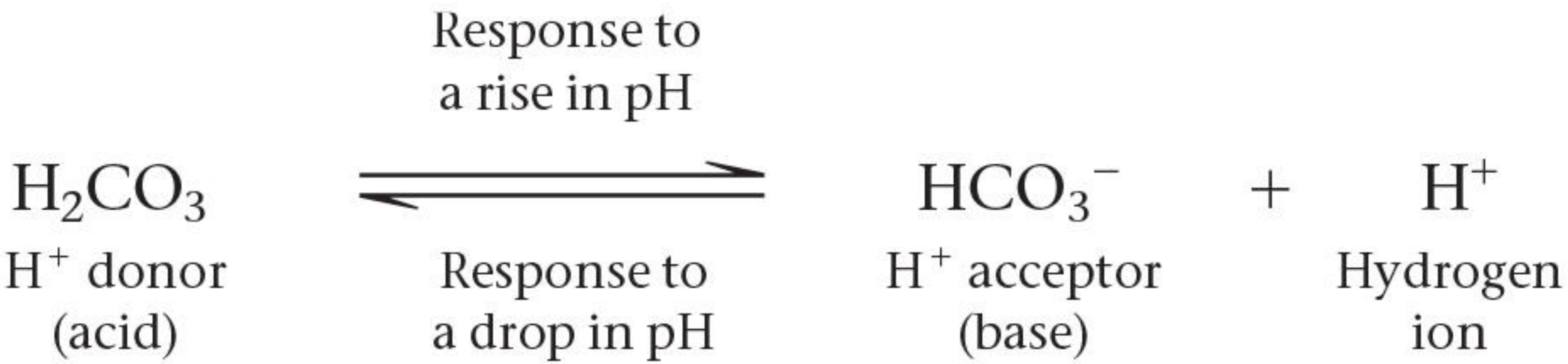

pH scale
0
1
Battery acid
2
Lemon juice,
gastric juice
3
Vinegar, cola
4
Tomato juice
5
Rainwater
6
Human urine
Saliva
7
Pure water
Increasingly ACIDIC
(Higher H+ concentration)
NEUTRAL
[H+] = [OH–]


NEUTRAL
$[H^+] = [OH^-]$
Increasingly BASIC
(Higher OH^- concentration)
7 Pure water
Human blood, tears
8 Seawater
9
10
Milk of magnesia
11
Household ammonia
12
Household bleach
13
Oven cleaner
14


H+ H+
H+ OH−
H+
OH− H+
H+ H+ H+
Acidic solution
OH− H+ OH−
H+ OH−
OH−
OH−
H+ H+ H+
Neutral solution
OH− OH−
OH− H+ OH−
OH−
OH− H+ OH−
BLEACH
Basic solution

Buffers

- The internal pH of most living cells is close to 7
- A slight change in pH can be harmful
- **Buffers** are substances that minimize changes in concentrations of H^+ and OH^- in a solution (i.e. buffers minimize changes in pH
- Most buffer solutions contain a weak acid and its corresponding base, which combine reversibly with H^+ ions

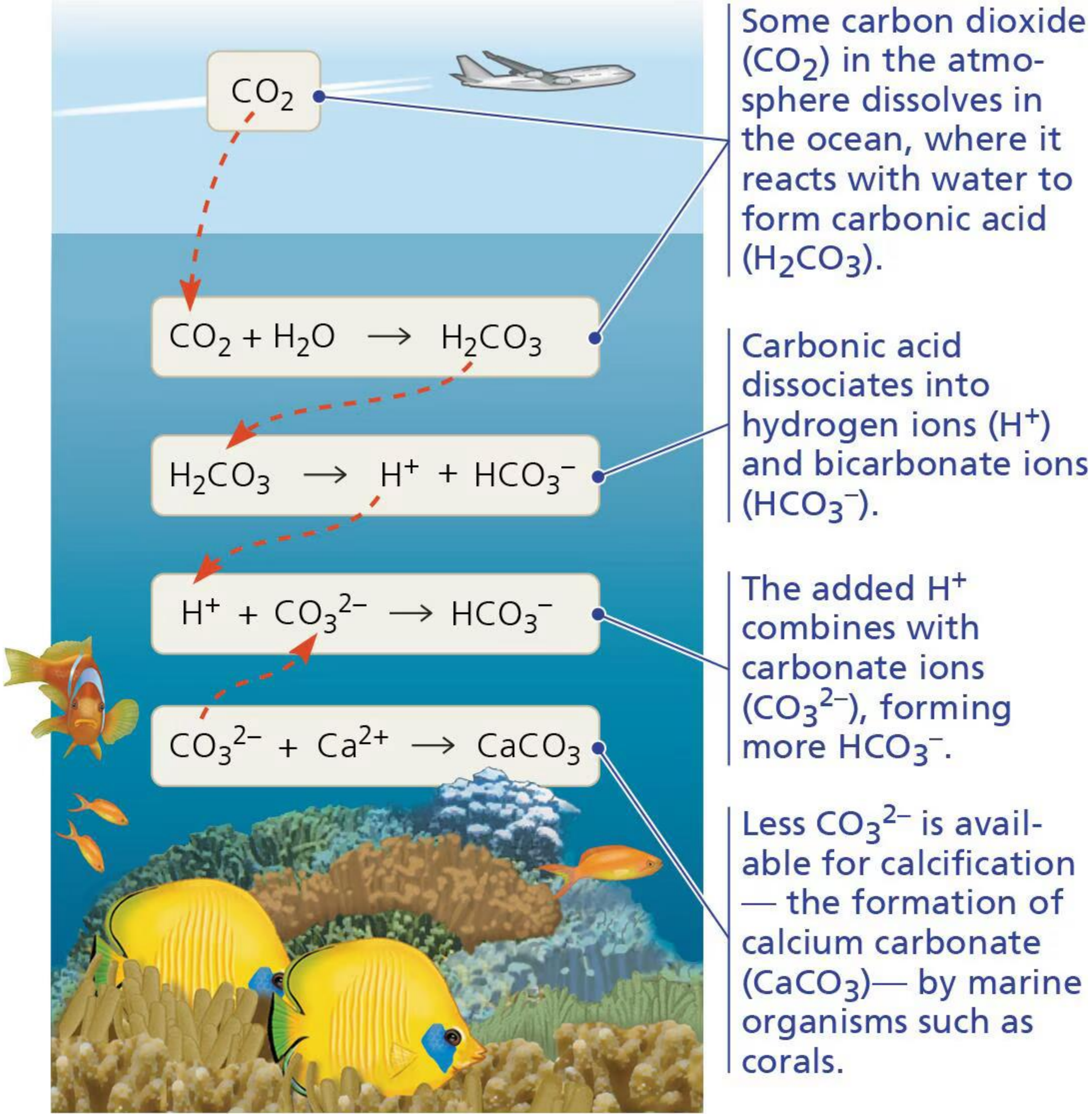


Ocean Acidification

- Human activities such as burning fossil fuels threaten water quality
- CO_2 is the main product of fossil fuel combustion
- About 25% of human-generated CO_2 is absorbed by the oceans

Ocean Acidification

- This reaction reduces the carbonate ion concentration available to corals and other shell-building animals.
- Carbonate is required for calcification (production of calcium carbonate - $CaCO_3$) by many marine organisms, including reef-building corals
- Researchers believe that ocean acidification is likely to cause “profound, ecosystem-wide changes in coral reefs”



Life on other Planets?

- Biologists seeking life on other planets have concentrated their search on planets that might have water
- More than 800 planets have been found outside our solar system; there is evidence that a few of them have water vapor
- Evidence of liquid water on Mars

Carbon: the backbone of life

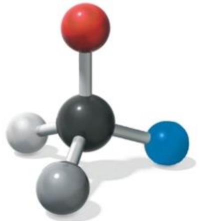
What makes carbon the basis for all biological molecules?

- Living organisms consist mostly of carbon-based compounds
- Carbon is unique in its ability to form large, complex, and varied molecules
- Proteins, DNA, carbohydrates, and other macro-molecules that distinguish living organisms are all composed of carbon compounds

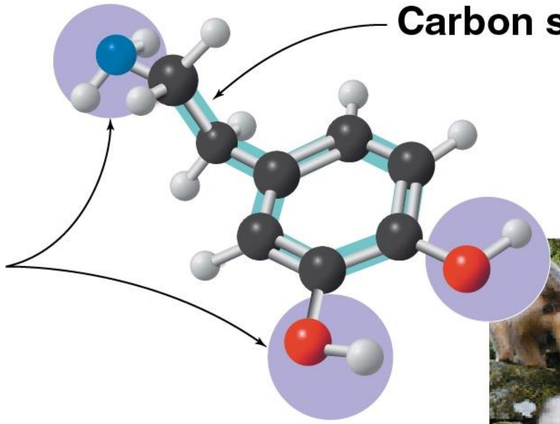
Carbon can form four bonds, and therefore can bond to up to four other atoms or groups of atoms.

Carbon can bond to other carbons, resulting in carbon skeletons. Carbon also commonly bonds to

H hydrogen   O oxygen   N nitrogen



The properties of a carbon-containing molecule depend on the arrangement of its carbon skeleton and on its chemical groups.

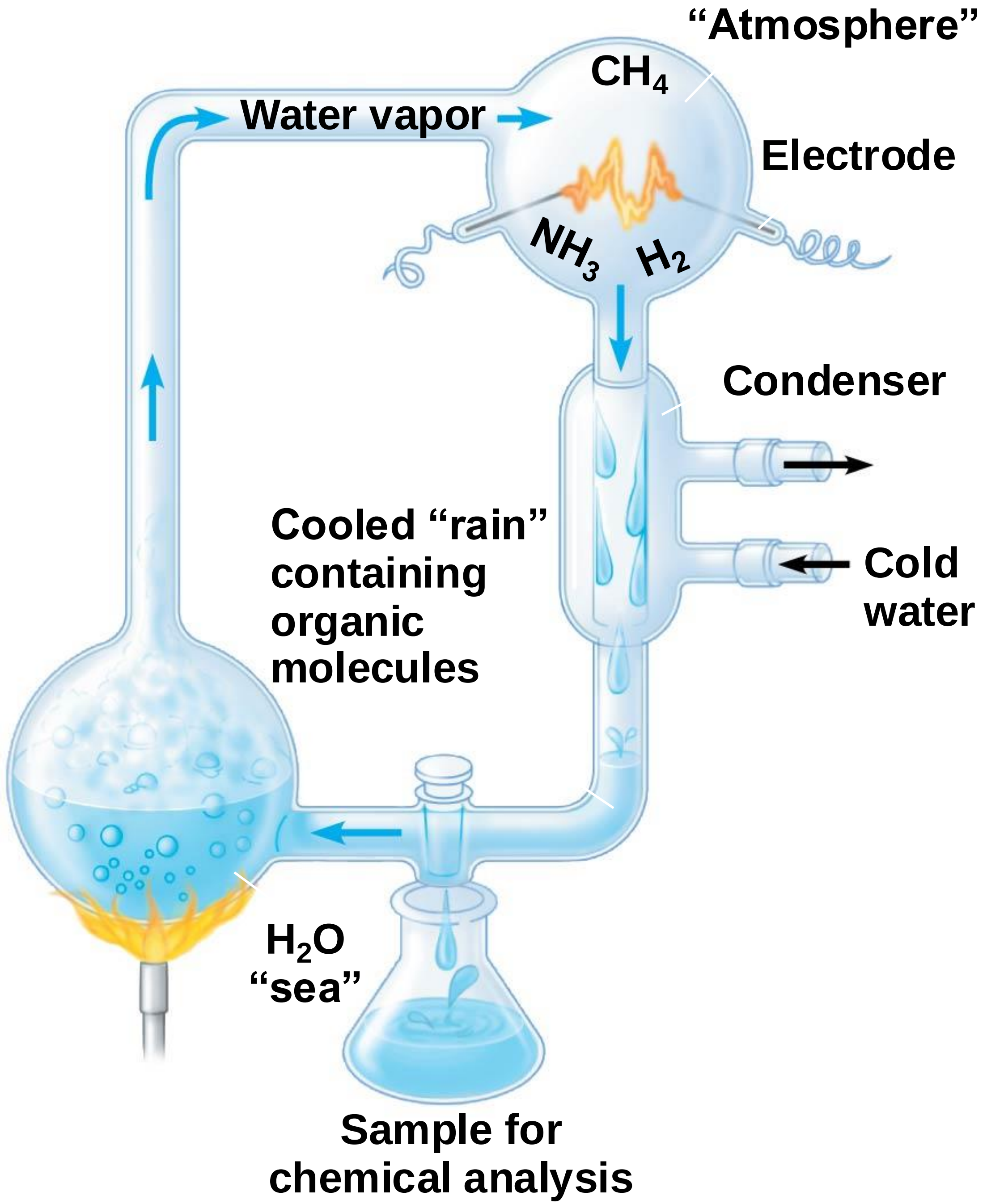


The signaling molecule shown here, dopamine, has many functions, including promoting mother-infant bonding.

Organic Molecules and the Origin of Life on Earth

- **Organic chemistry** is the study of compounds that contain carbon, regardless of origin
- Organic compounds range from simple molecules to giant ones
- Stanley Miller's classic experiment demonstrated the **abiotic synthesis of organic compounds**
- Support the idea that abiotic synthesis of organic compounds could have been a stage in the origin of life

Eg. near volcanoes

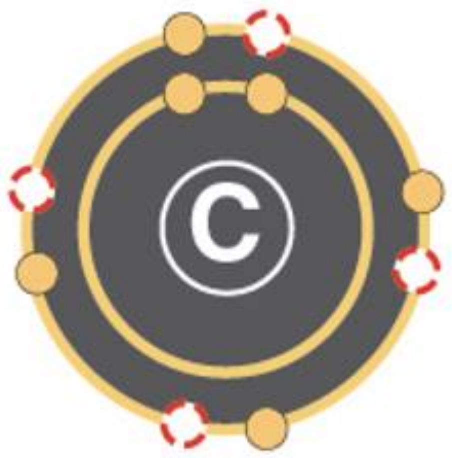


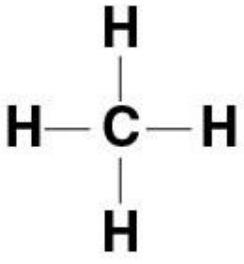
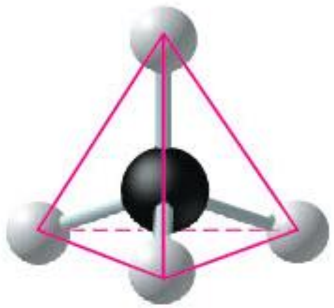
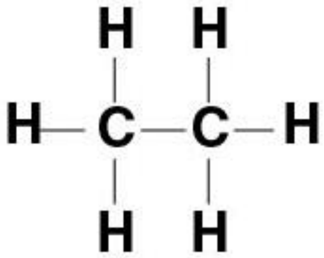
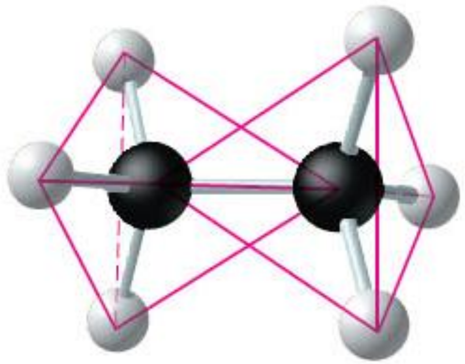
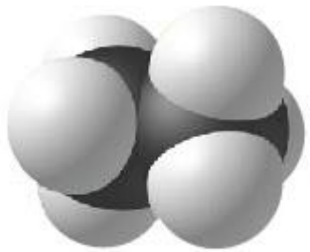
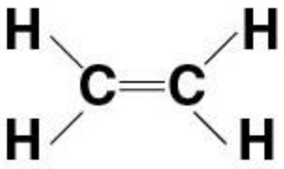
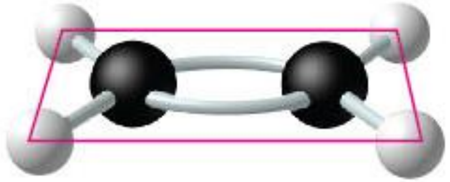
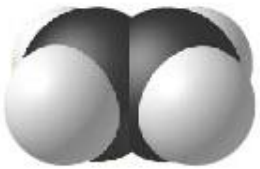
Organic Molecules and the Origin of Life on Earth

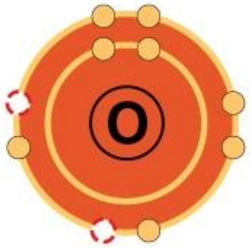
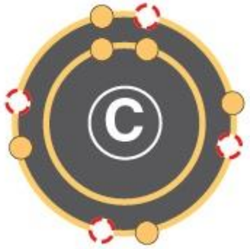
- The overall percentages of the major elements of life—C, H, O, N, S, and P—are quite uniform from one organism to another
- Because of carbon's ability to form four bonds, these building blocks can be used to make an inexhaustible variety of organic molecules
- The great diversity of organisms on the planet is due to the versatility of carbon

Carbon atoms can form diverse molecules by bonding to four other atoms

- Electron configuration is the key to an atom’s characteristics
- Electron configuration determines the kinds and number of bonds an atom will form with other atoms
- With **four valence electrons**, carbon can form **four covalent bonds** with a variety of atoms
- This makes large, complex molecules possible



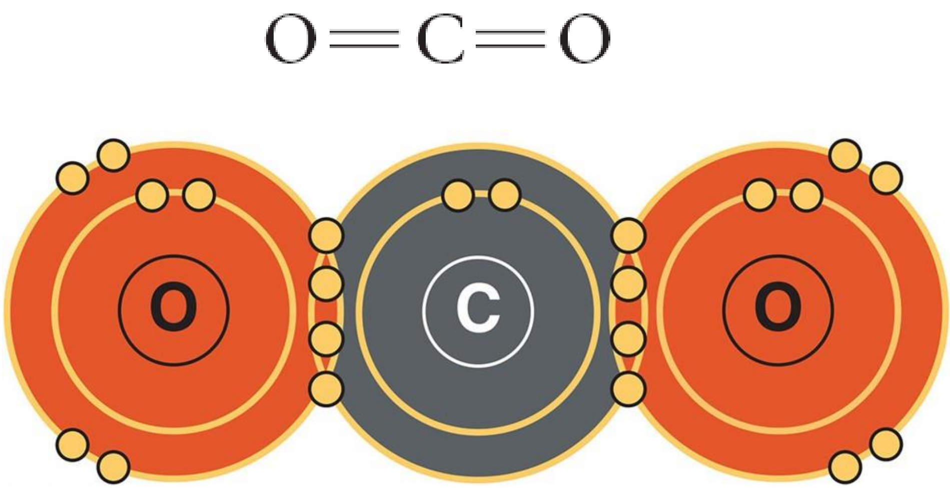
Molecule and Molecular Shape	Molecular Formula	Structural Formula	Ball-and-Stick Model (molecular shape in pink)	Space-Filling Model
(a) Methane	CH_4			
(b) Ethane	C_2H_6			
(c) Ethene (ethylene)	C_2H_4			

	Hydrogen	Oxygen	Nitrogen	Carbon
Lewis dot structure showing existing valence electrons				
Electron distribution diagram with red circles showing electrons needed to fill the valence shell				
Number of electrons needed to fill the valence shell	1	2	3	4
Valence: Number of bonds the element can form	1	2	3	4

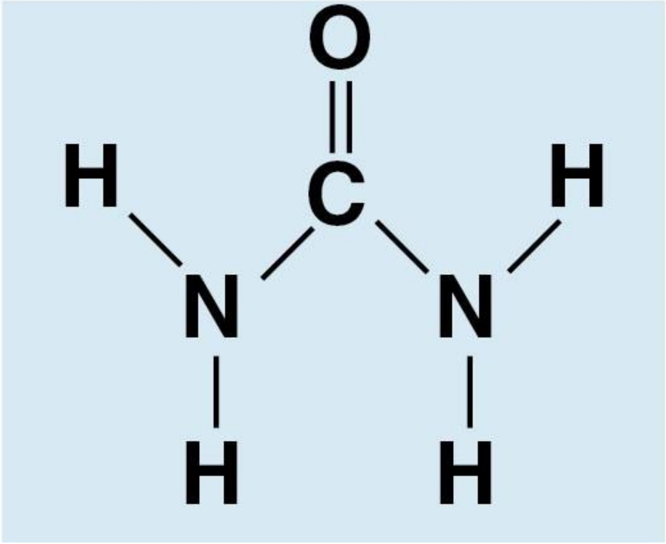
- The electron configuration of carbon gives it covalent compatibility with many different elements
  - The most frequent bonding partners of carbon are hydrogen, oxygen, and nitrogen
    - These are the building code for the architecture of living molecules

Molecular Diversity Arises from Variation in Carbon Skeletons

- Carbon atoms can partner with atoms other than hydrogen:
  - Carbon dioxide: CO_2

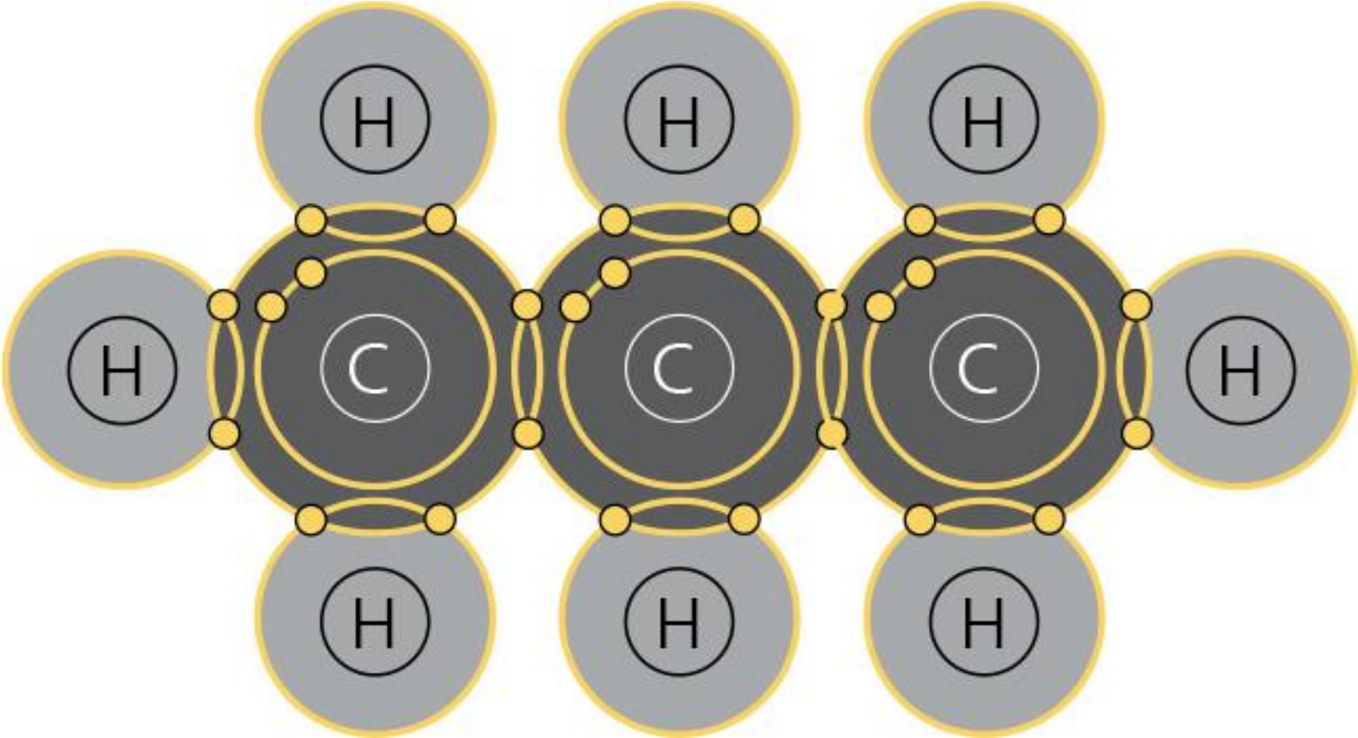


  - Urea CO(NH2)2



Molecular Diversity Arises from Variation in Carbon Skeletons

- Carbon can also use one or more valence electrons to form covalent bonds to other carbon atoms, linking them into chains: C_3H_8



Molecular Diversity Arises from Variation in Carbon Skeletons

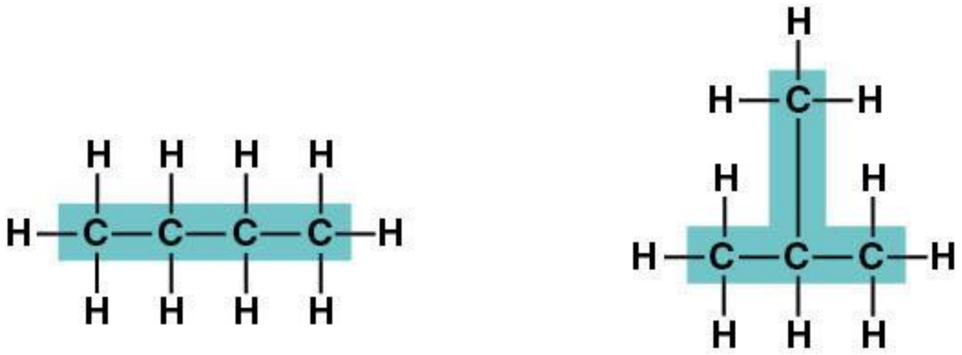
- Carbon chains form the skeletons of most organic molecules
- Carbon chains vary in length and shape

(a) Length

Ethane　　Propane

Carbon skeletons vary in length.

(b) Branching



Butane　　2-Methylpropane (commonly called isobutane)

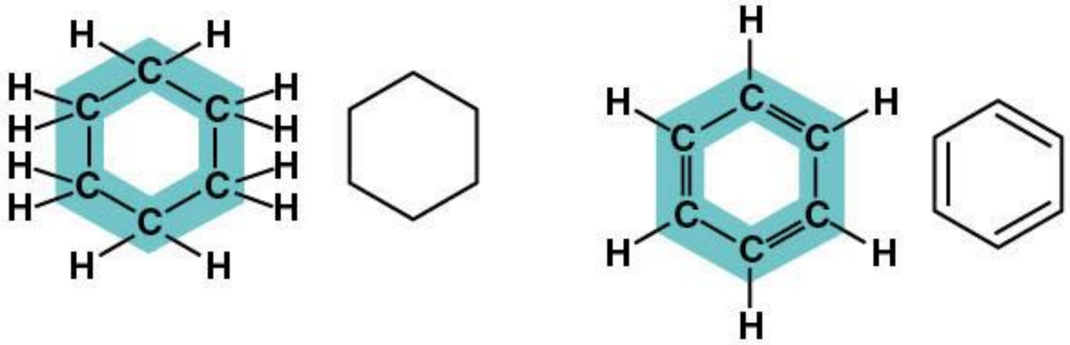
Skeletons may be unbranched or branched.

(c) Double bond position

1-Butene　　2-Butene

The skeleton may have double bonds, which can vary in location.

(d) Presence of rings



Cyclohexane　　Benzene

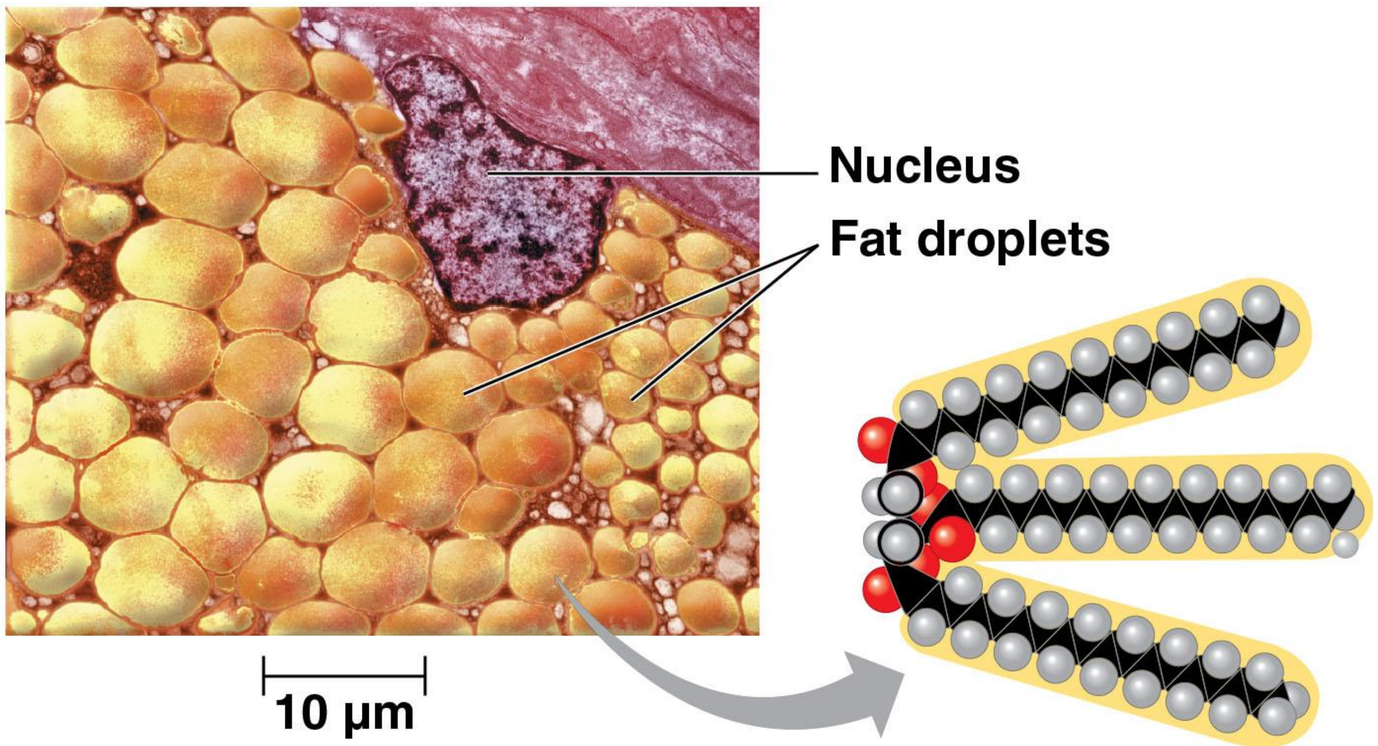
Some carbon skeletons are arranged in rings. In the abbreviated structural formula for each compound (to its right), each corner represents a carbon and its attached hydrogens.

Molecular Diversity Arises from Variation in Carbon Skeletons

[redacted]

Hydrocarbons

- Hydrocarbons are organic molecules consisting of only carbon and hydrogen
- Many organic molecules, such as fats, have hydrocarbon components
- Hydrocarbons can undergo reactions that release a large amount of energy

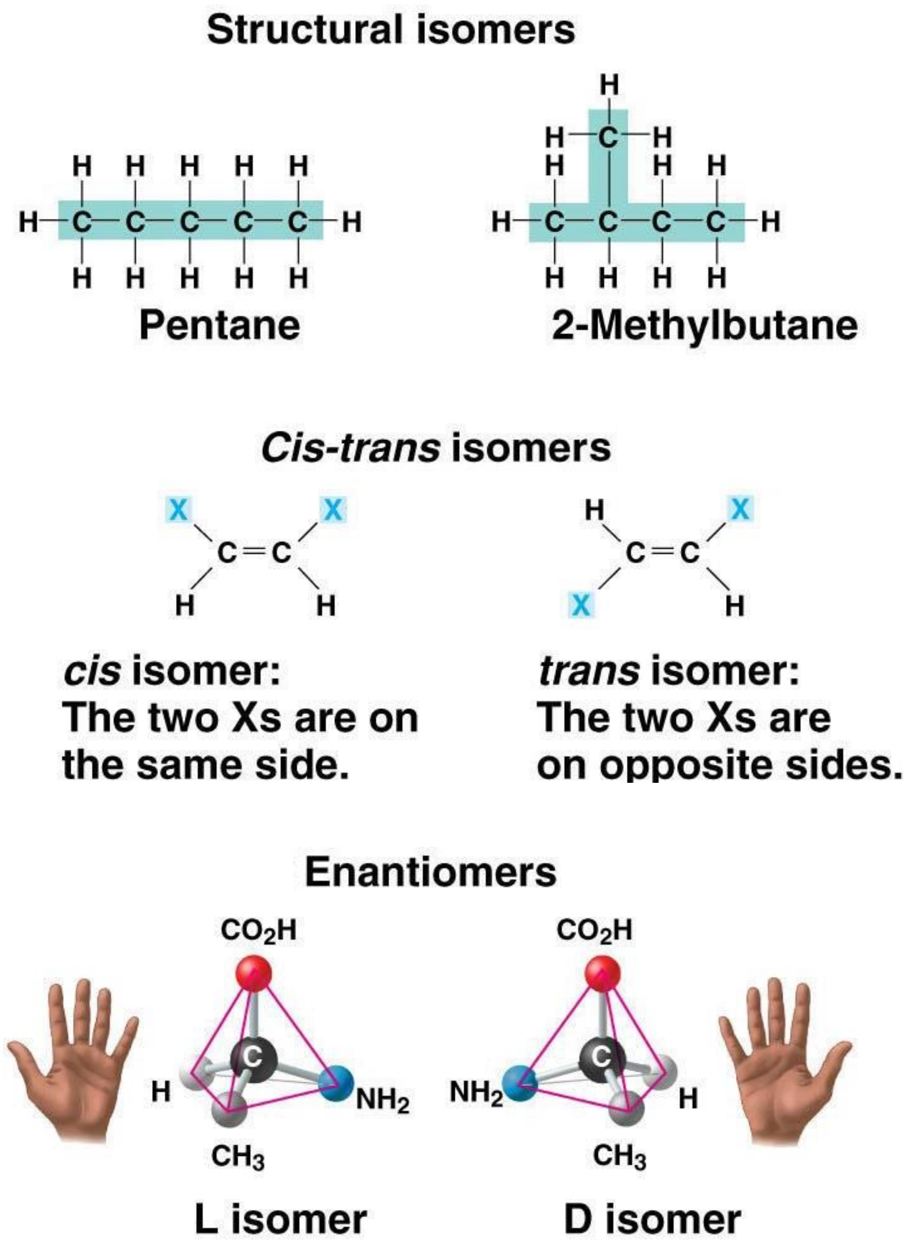


(a) Part of a human adipose cell (b) A fat molecule

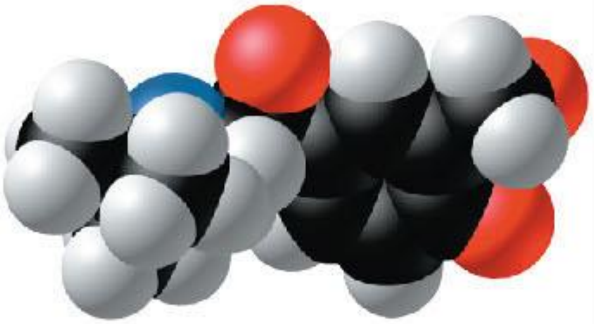
Isomers

Isomers are compounds with the same molecular formula but different structures and properties

- Structural isomers have different covalent arrangements of their atoms
- Cis-trans isomers (also called geometric isomers) have the same covalent bonds but differ in their spatial arrangements
- Enantiomers are isomers that are mirror images of each other



[redacted]

Drug	Effects	Effective Enantiomer	Ineffective Enantiomer
Ibuprofen	Reduces inflammation and pain	 *S*-Ibuprofen	 *R*-Ibuprofen
Albuterol	Relaxes bronchial (airway) muscles, improving airflow in asthma patients	 *R*-Albuterol	 *S*-Albuterol

Chemical groups are key to molecular function

The seven functional groups that are most important in the chemistry of life are the following:

- Hydroxyl group
- Carbonyl group
- Carboxyl group
- Amino group
- Sulfhydryl group
- Phosphate group
- Methyl group

Chemical groups are key to molecular function

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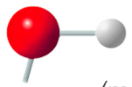
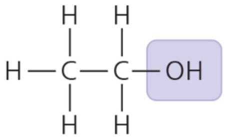
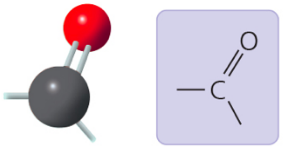
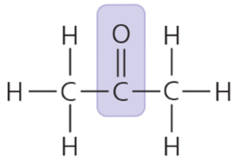
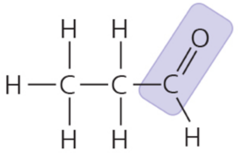
- **Hydroxyl group**
- Carbonyl group
- Carboxyl group
- Amino group
- Sulfhydryl group
- Phosphate group
- Methyl group

Chemical Group	Group Properties and Compound Name	Examples
Hydroxyl group (—OH)  —OH (may be written HO—)	Is polar due to electronegative oxygen. Forms hydrogen bonds with water, helping dissolve compounds such as sugars. Compound name: **Alcohol** (specific name usually ends in *-ol*)	 **Ethanol**, the alcohol present in alcoholic beverages

Chemical groups are key to molecular function

The seven functional groups that are most important in the chemistry of life are the following:

- Hydroxyl group
- **Carbonyl group**
- Carboxyl group
- Amino group
- Sulfhydryl group
- Phosphate group
- Methyl group

Chemical Group	Group Properties and Compound Name	Examples
Carbonyl group (>C═O) 	Sugars with ketone groups are called ketoses; those with aldehydes are called aldoses. Compound name: **Ketone** (carbonyl group is within a carbon skeleton) or **aldehyde** (carbonyl group is at the end of a carbon skeleton)	 **Acetone**, the simplest ketone  **Propanal**, an aldehyde

Chemical groups are key to molecular function

The seven functional groups that are most important in the chemistry of life are the following:

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- **Carboxyl group**
- Amino group
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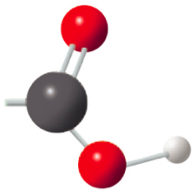
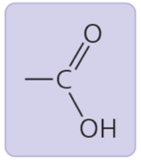
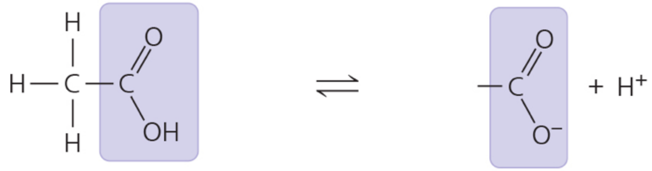
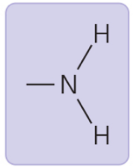
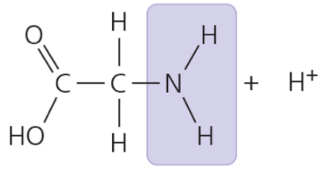
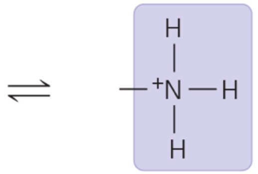
- Phosphate group
- Methyl group

Chemical Group	Group Properties and Compound Name	Examples
Carboxyl group (—COOH)  	Acts as an acid (can donate H^+) because the covalent bond between oxygen and hydrogen is so polar. Compound name: **Carboxylic acid**, or **organic acid**	 **Acetic acid**, which gives vinegar its sour taste Ionized form of —COOH (carboxylate ion), found in cells

Chemical groups are key to molecular function

The seven functional groups that are most important in the chemistry of life are the following:

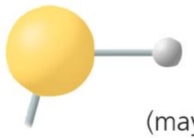
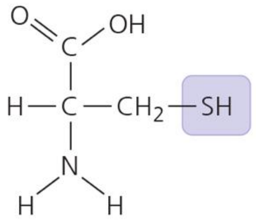
- Hydroxyl group
- Carbonyl group
- Carboxyl group
- **Amino group**
- Sulfhydryl group
- Phosphate group
- Methyl group

Chemical Group	Group Properties and Compound Name	Examples
Amino group (—NH_2)  	Acts as a base; can pick up an H^+ from the surrounding solution (water, in living organisms). Compound name: **Amine**	 **Glycine**, an amino acid (note its carboxyl group)  Ionized form of —NH_2, found in cells

Chemical groups are key to molecular function

The seven functional groups that are most important in the chemistry of life are the following:

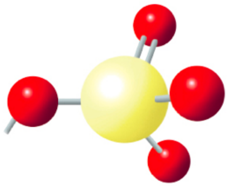
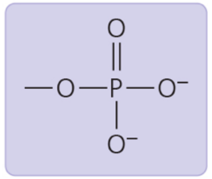
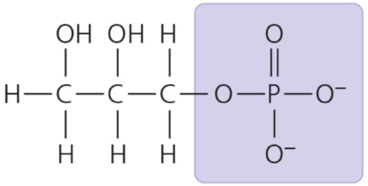
- Hydroxyl group
- Carbonyl group
- Carboxyl group
- Amino group
- **Sulfhydryl group**
- Phosphate group
- Methyl group

Chemical Group	Group Properties and Compound Name	Examples
Sulfhydryl group (—SH)  —SH (may be written HS —)	Two —SH groups can react, forming a "cross-link" that helps stabilize protein structure. Hair protein cross-links maintain the straightness or curliness of hair; in hair salons, "permanent" treatments break cross-links, then re-form them while the hair is in the desired shape. Compound name: **Thiol**	 **Cysteine**, a sulfur-containing amino acid

Chemical groups are key to molecular function

The seven functional groups that are most important in the chemistry of life are the following:

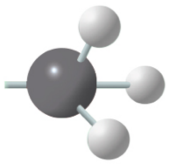
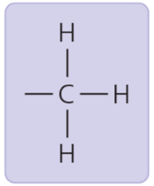
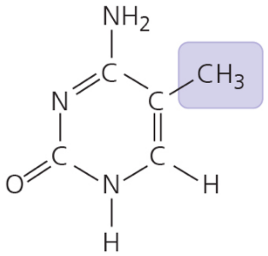
- Hydroxyl group
- Carbonyl group
- Carboxyl group
- Amino group
- Sulfhydryl group
- **Phosphate group**
- Methyl group

Chemical Group	Group Properties and Compound Name	Examples
Phosphate group ($—OPO_3^{2-}$)  	Contributes negative charge (1– when positioned inside a chain of phosphates; 2– when at the end). When attached, confers on a molecule the ability to react with water, releasing energy. Compound name: **Organic phosphate**	 **Glycerol phosphate**, which takes part in many important chemical reactions in cells

Chemical groups are key to molecular function

The seven functional groups that are most important in the chemistry of life are the following:

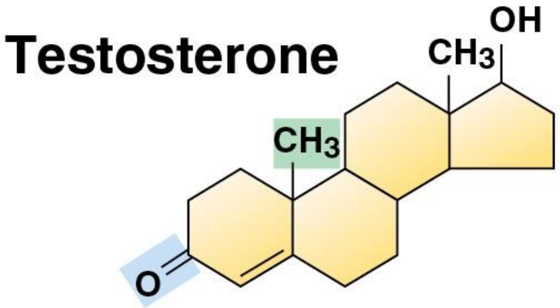
- Hydroxyl group
- Carbonyl group
- Carboxyl group
- Amino group
- Sulfhydryl group
- Phosphate group
- **Methyl group**

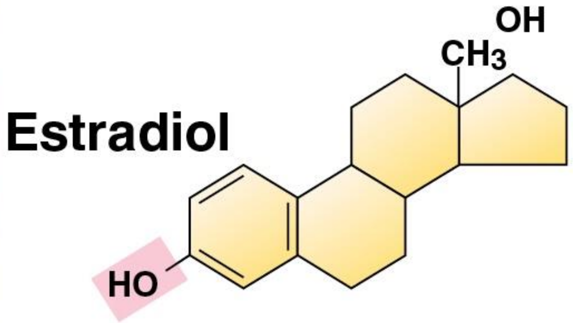
Chemical Group	Group Properties and Compound Name	Examples
Methyl group (—CH_3)  	Affects the expression of genes when bonded to DNA or to proteins that bind to DNA. Affects the shape and function of male and female sex hormones. Compound name: **Methylated compound**	 **5-Methylcytosine**: Cytosine, a component of DNA, has been modified by addition of a methyl group.

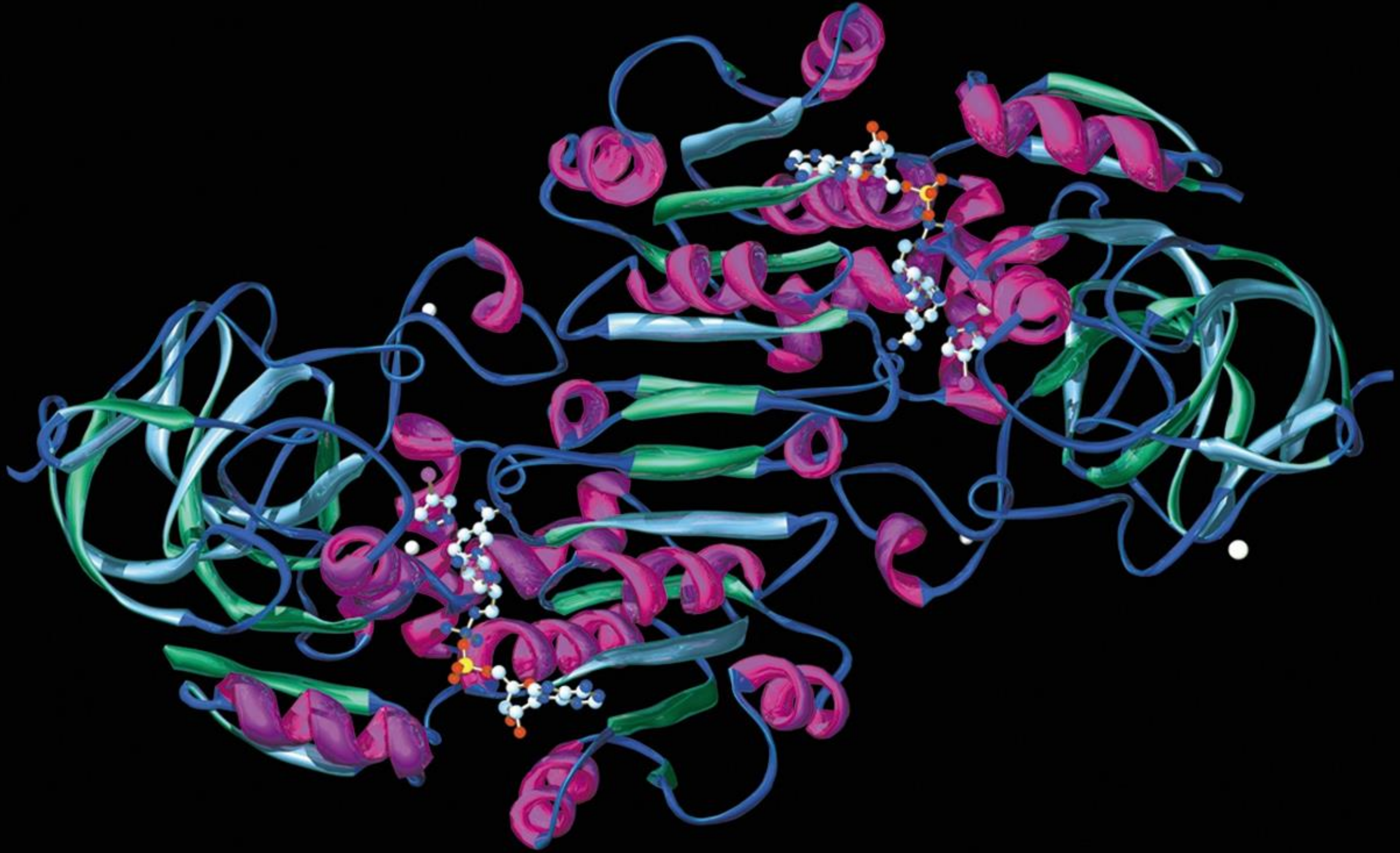
[redacted]

Chemical Groups Are Key to the Functioning of Biological Molecules

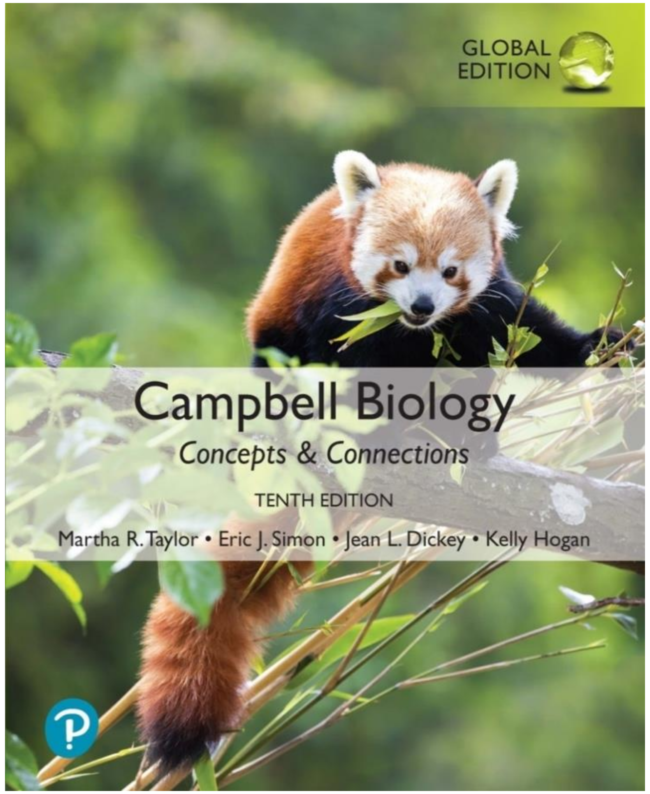
- The sex hormones testosterone and estradiol (estrogen) differ only in functional groups.

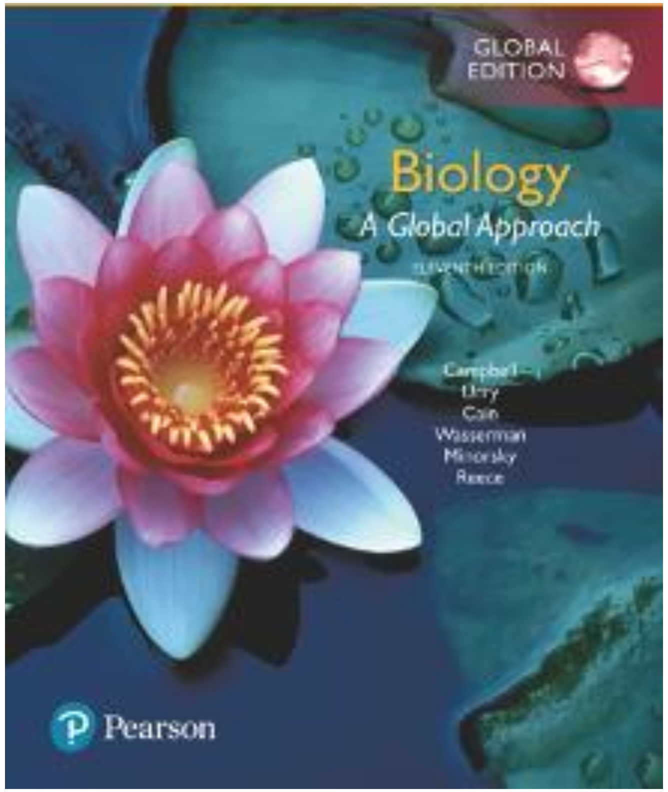


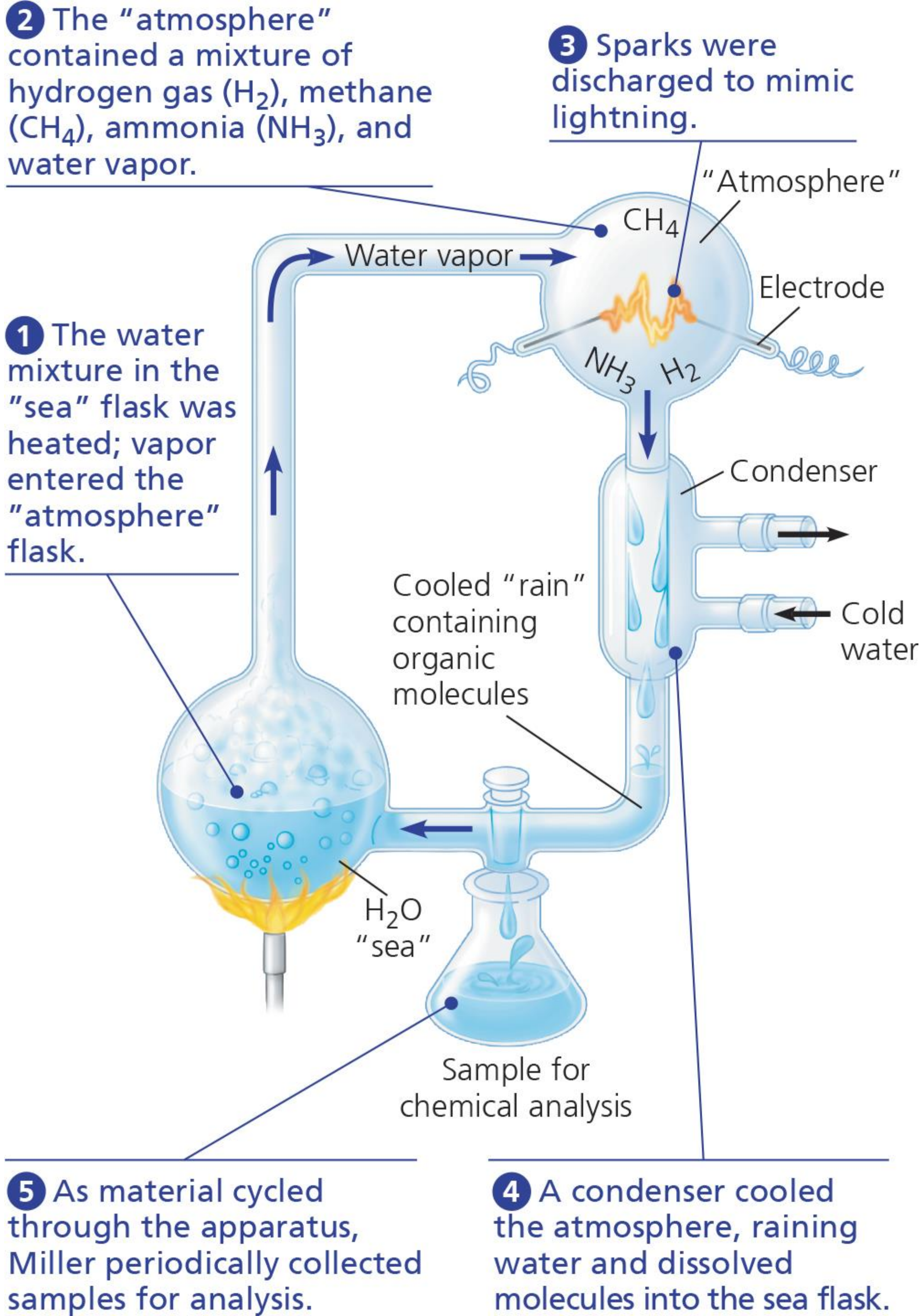




Sources


GLOBAL EDITION
Campbell Biology
Concepts & Connections
TENTH EDITION
Martha R. Taylor • Eric J. Simon • Jean L. Dickey • Kelly Hogan


GLOBAL EDITION
Biology
A Global Approach
Pearson


2 The "atmosphere" contained a mixture of hydrogen gas (H_2), methane (CH_4), ammonia (NH_3), and water vapor.
3 Sparks were discharged to mimic lightning.
"Atmosphere"
CH_4
Water vapor
Electrode
NH_3
H_2
1 The water mixture in the "sea" flask was heated; vapor entered the "atmosphere" flask.
Condenser
Cold water
Cooled "rain" containing organic molecules
H_2O "sea"
Sample for chemical analysis
5 As material cycled through the apparatus, Miller periodically collected samples for analysis.
4 A condenser cooled the atmosphere, raining water and dissolved molecules into the sea flask.