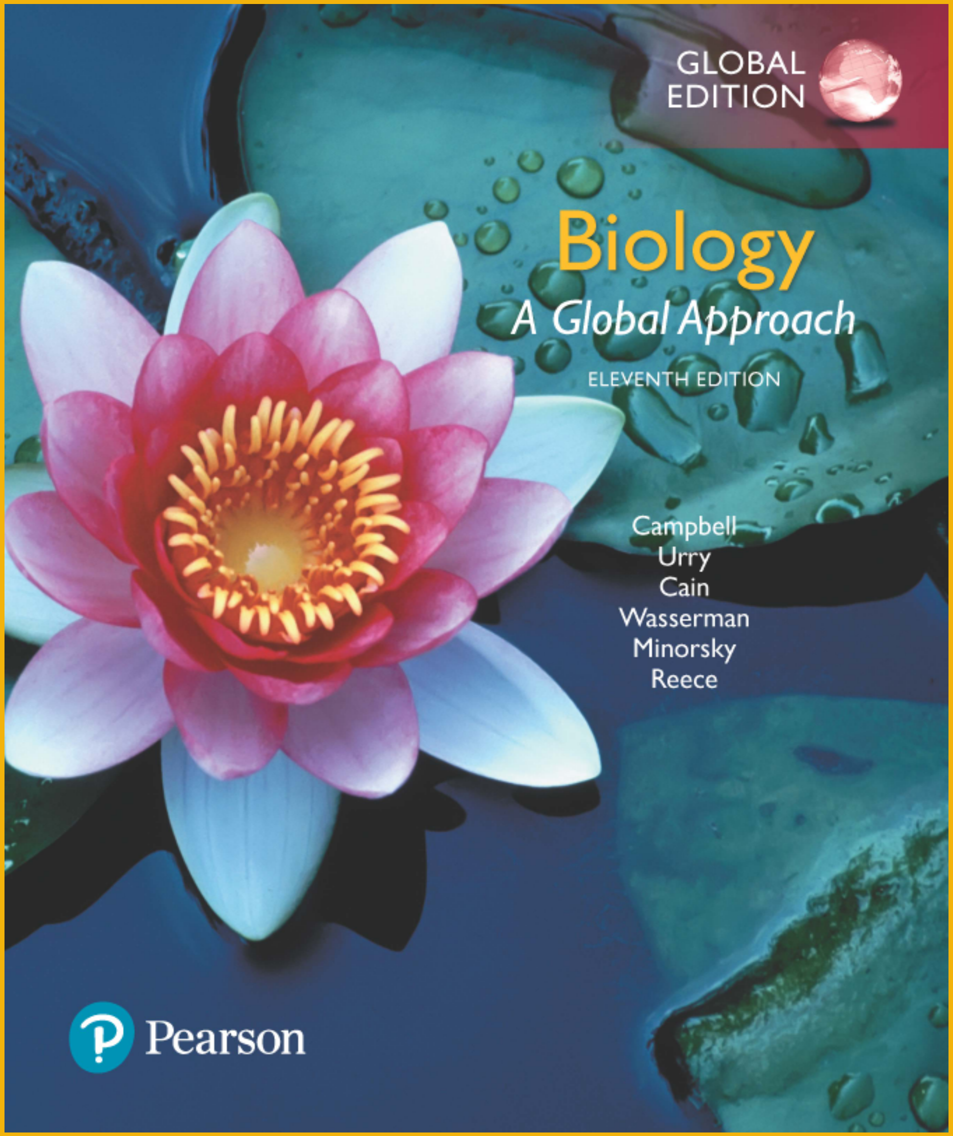


Chapter 3

The Chemistry of Water

Lecture Presentations by
Nicole Tunbridge and
Kathleen Fitzpatrick

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

Figure 3.1

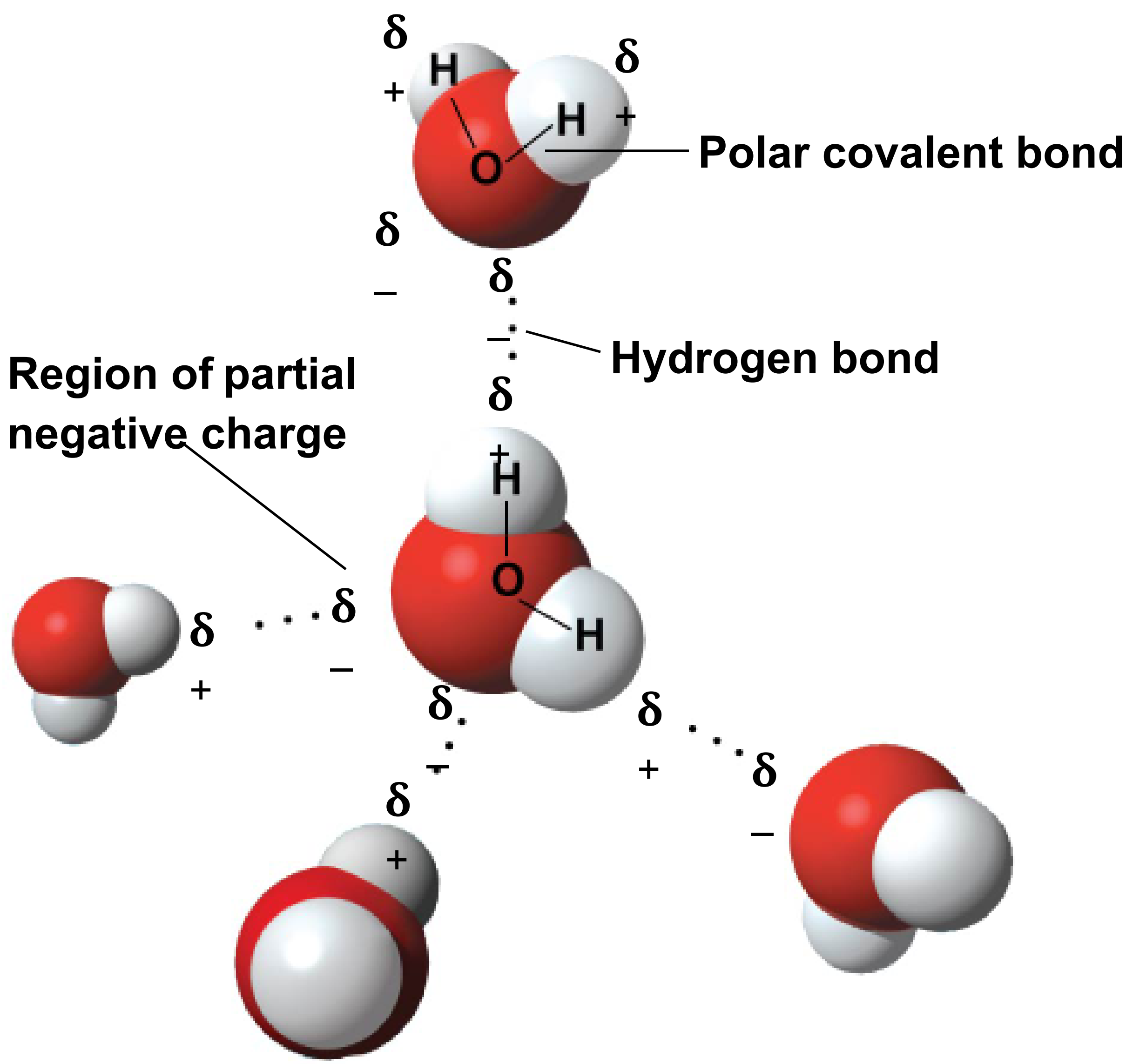
Figure 3.1a

Black guillemots, threatened by climate change

Concept 3.1: Polar covalent bonds in water molecules result in hydrogen bonding

- In the water molecule, the electrons of the **polar covalent bonds** spend more time near the oxygen than the hydrogen
- The water molecule is thus a **polar molecule**: The overall charge is unevenly distributed
- Polarity allows water molecules to form hydrogen bonds with each other

Figure 3.2



δ
+
H
δ
H
+
O
Polar covalent bond
δ
–
δ
–
Hydrogen bond
δ
Region of partial
negative charge
+
H
O
H
δ
+
δ
–
δ
–
δ
+
δ
+
δ
–
δ
+

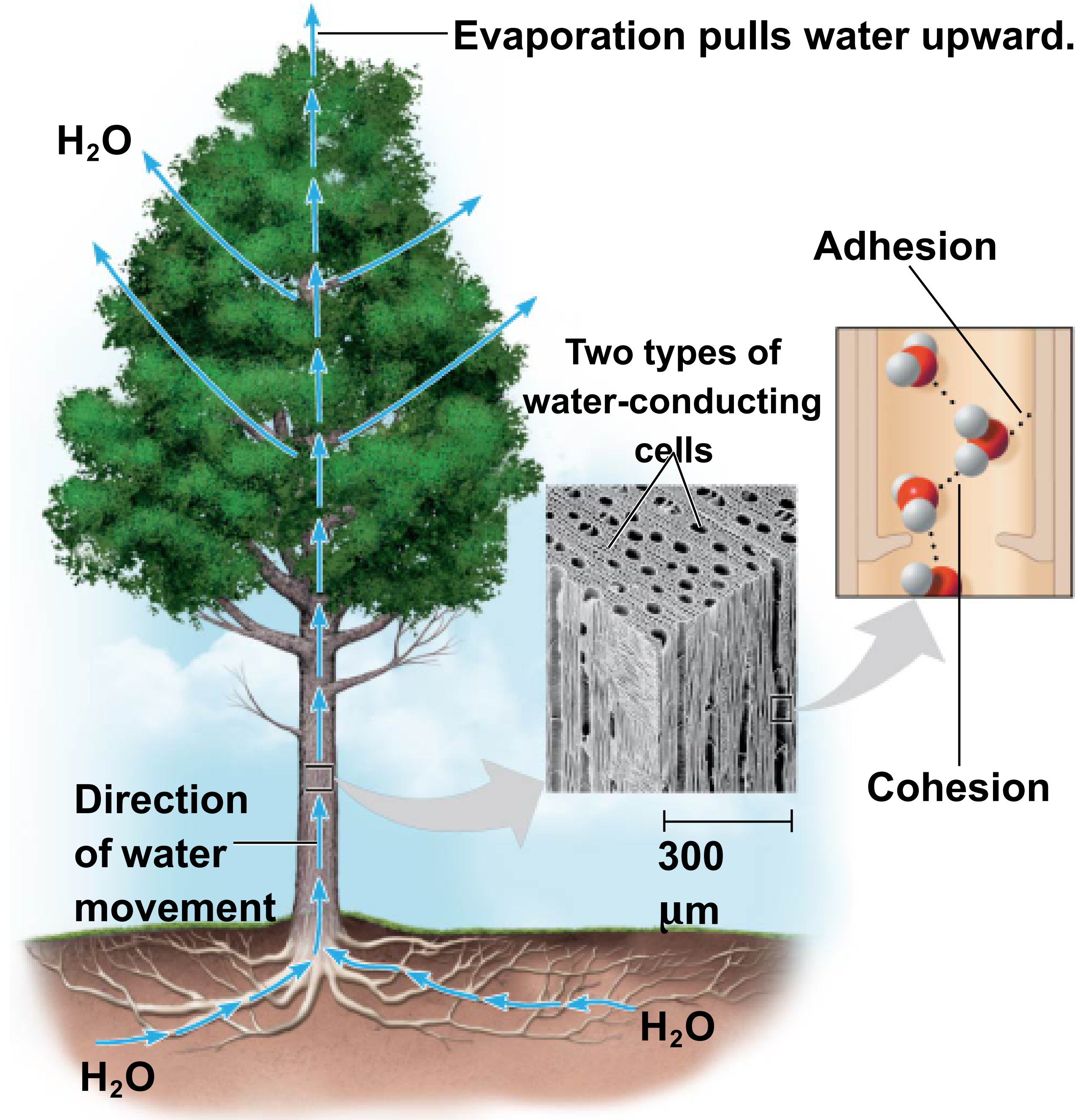
Concept 3.2: Four emergent properties of water contribute to Earth's suitability for life

- Four of water's properties that facilitate an environment for life are
  - Cohesive behavior
  - Ability to moderate temperature
  - Expansion upon freezing
  - Versatility as a solvent

Cohesion of Water Molecules

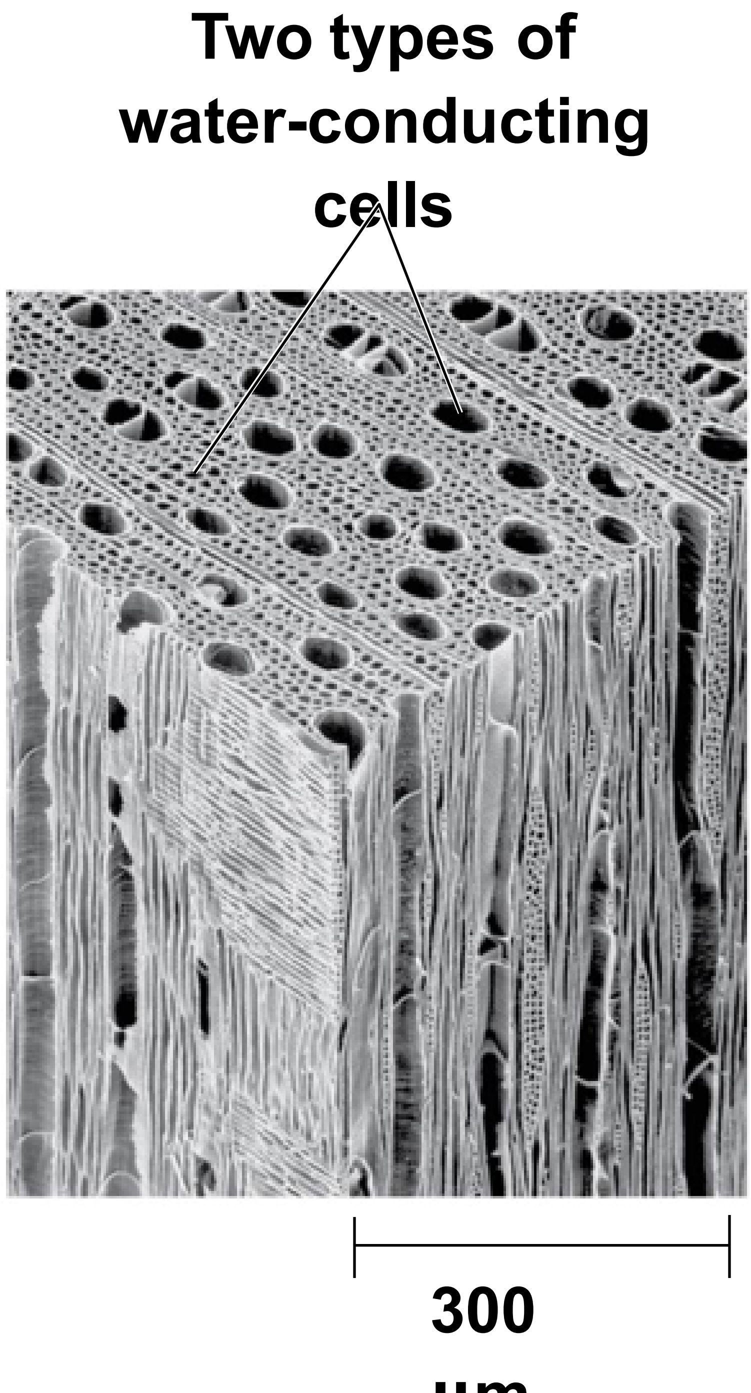
- Collectively, hydrogen bonds hold water molecules together, a phenomenon called **cohesion**
- Cohesion helps the transport of water against gravity in plants
- **Adhesion** is an attraction between different substances, for example, between water and plant cell walls

Figure 3.3

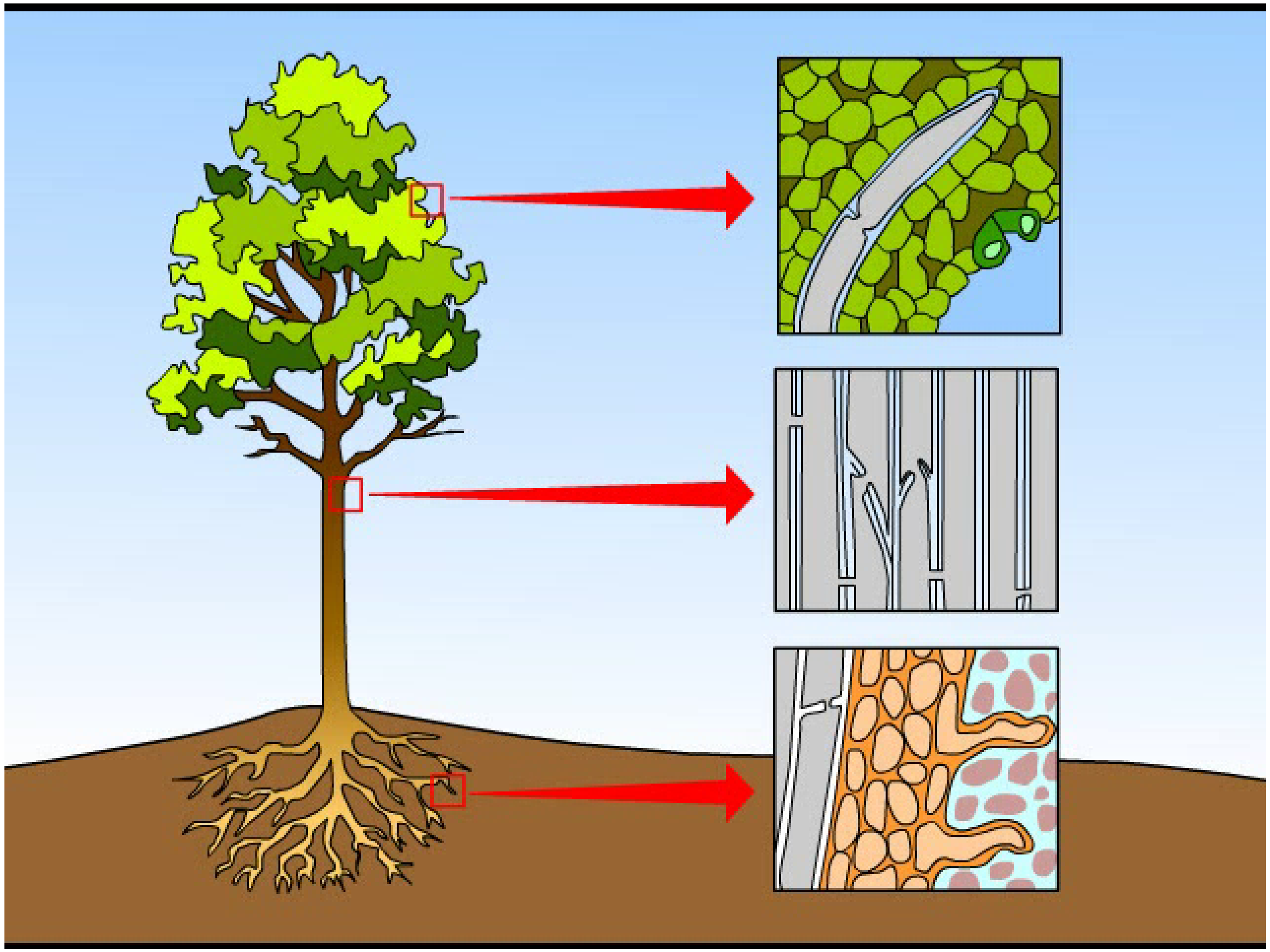


Evaporation pulls water upward.
H_2O
Adhesion
Two types of water-conducting cells
Direction of water movement
300 µm
Cohesion
H_2O
H_2O

Figure 3.3a



Animation: Water Transport in Plants



- **Surface tension** is 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

Figure 3.4

Moderation of Temperature by Water

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

Temperature and Heat

- **Kinetic energy** is the energy of motion
- The kinetic energy associated with random motion of atoms or molecules is called **thermal energy**
- **Temperature** represents the average kinetic energy of the molecules in a body of matter
- Thermal energy in transfer from one body of matter to another is defined as **heat**

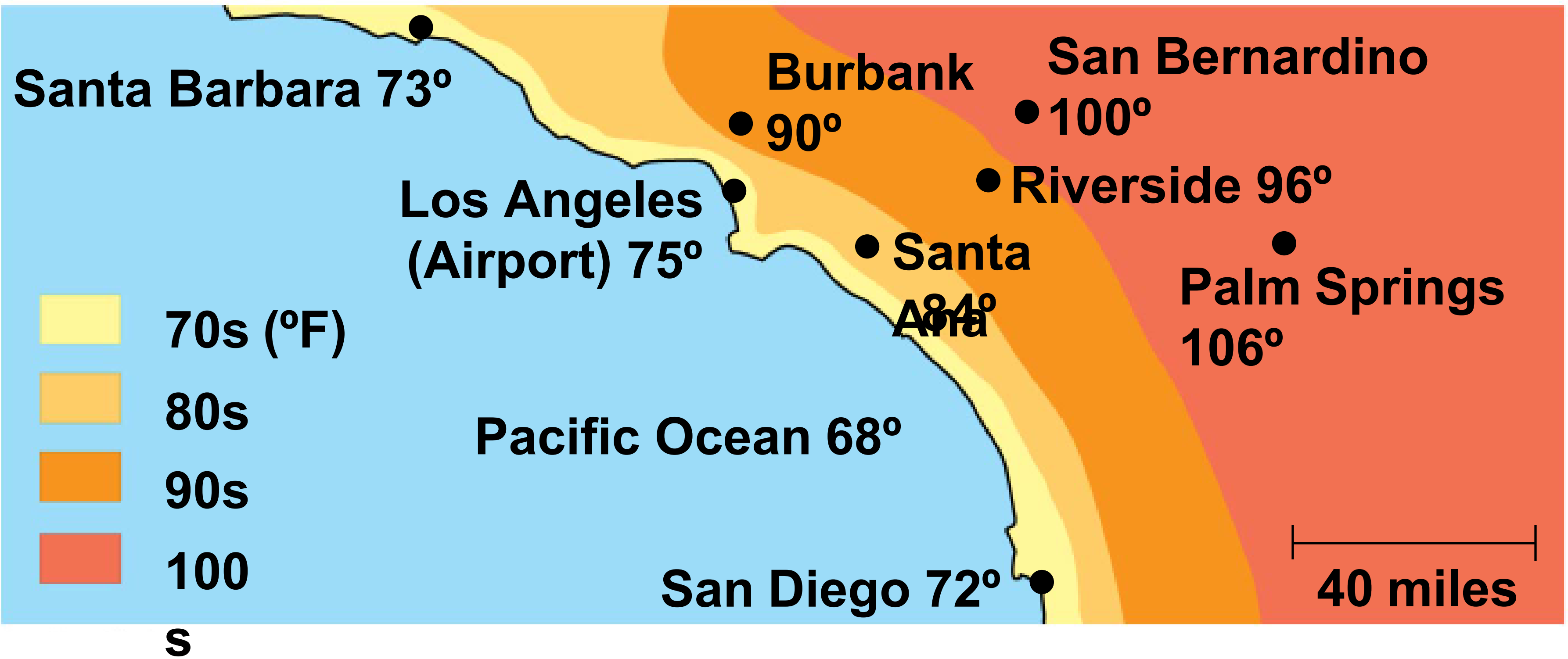
- A **calorie** (**cal**) is the amount of heat required to raise the temperature of 1 g of water by 1ºC
- It is also the amount of heat released when 1 g of water cools by 1ºC
- The "Calories" on food packages are actually **kilocalories** (**kcal**); 1 kcal = 1,000 cal
- The **joule** (**J**) is another unit of energy; 1 J = 0.239 cal, or 1 cal = 4.184 J

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 1ºC
- The specific heat of water is 1 cal/(g · ºC)
- 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

Figure 3.5



Santa Barbara 73º
Burbank
90º
San Bernardino
100º
Los Angeles
(Airport) 75º
Riverside 96º
Santa
Ana
84º
Palm Springs
106º
70s (ºF)
80s
90s
100
s
Pacific Ocean 68º
San Diego 72º
40 miles

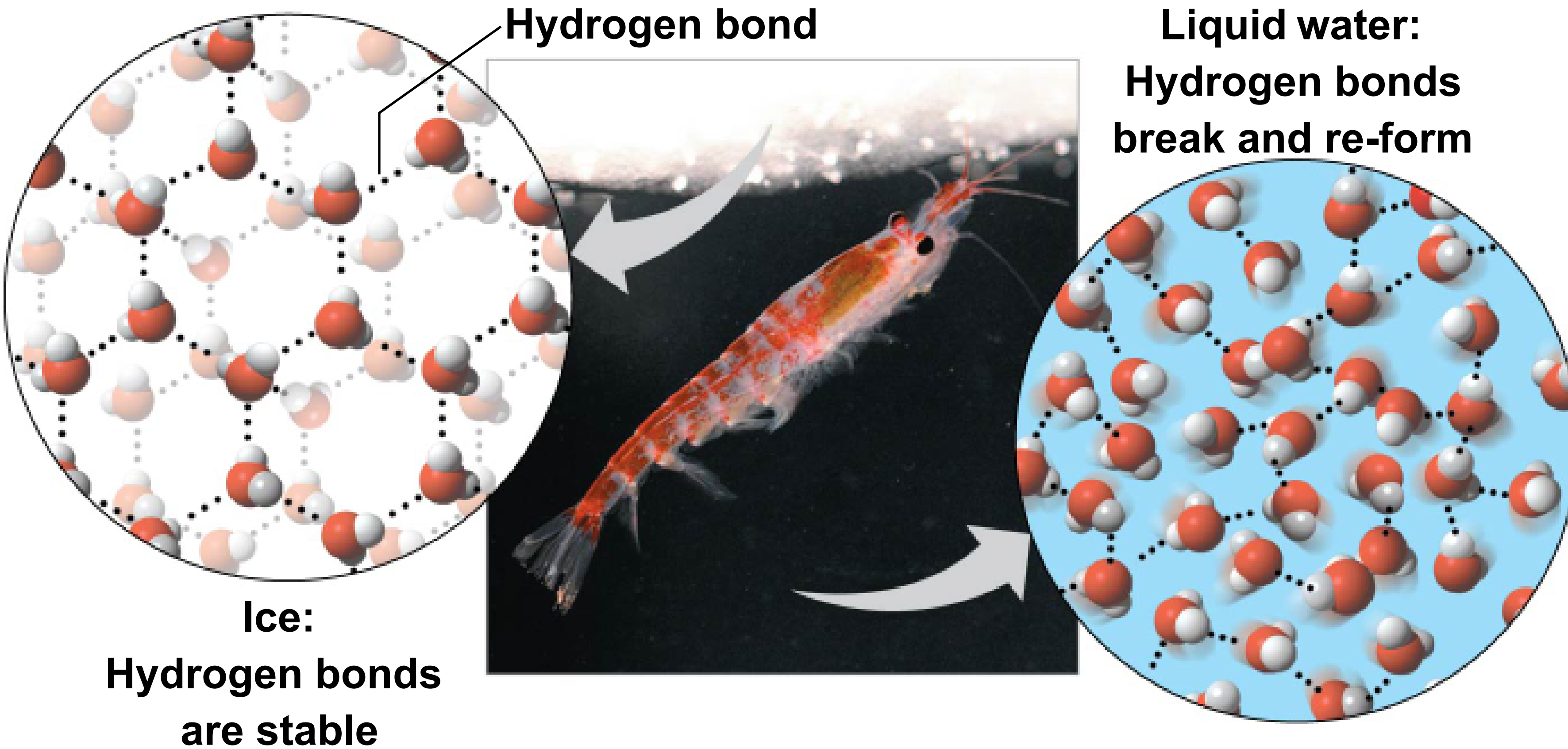
Evaluative Cooling

- Evaporation (or 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, a process called **evaporative cooling**
- Evaporative cooling of water helps stabilize temperatures in organisms and bodies of water

Floating of Ice on Liquid Water

- Ice floats in liquid water because hydrogen bonds in ice are more “ordered,” making ice less dense than water
- Water reaches its greatest density at 4ºC
- If ice sank, all bodies of water would eventually freeze solid, making life impossible on Earth

Figure 3.6

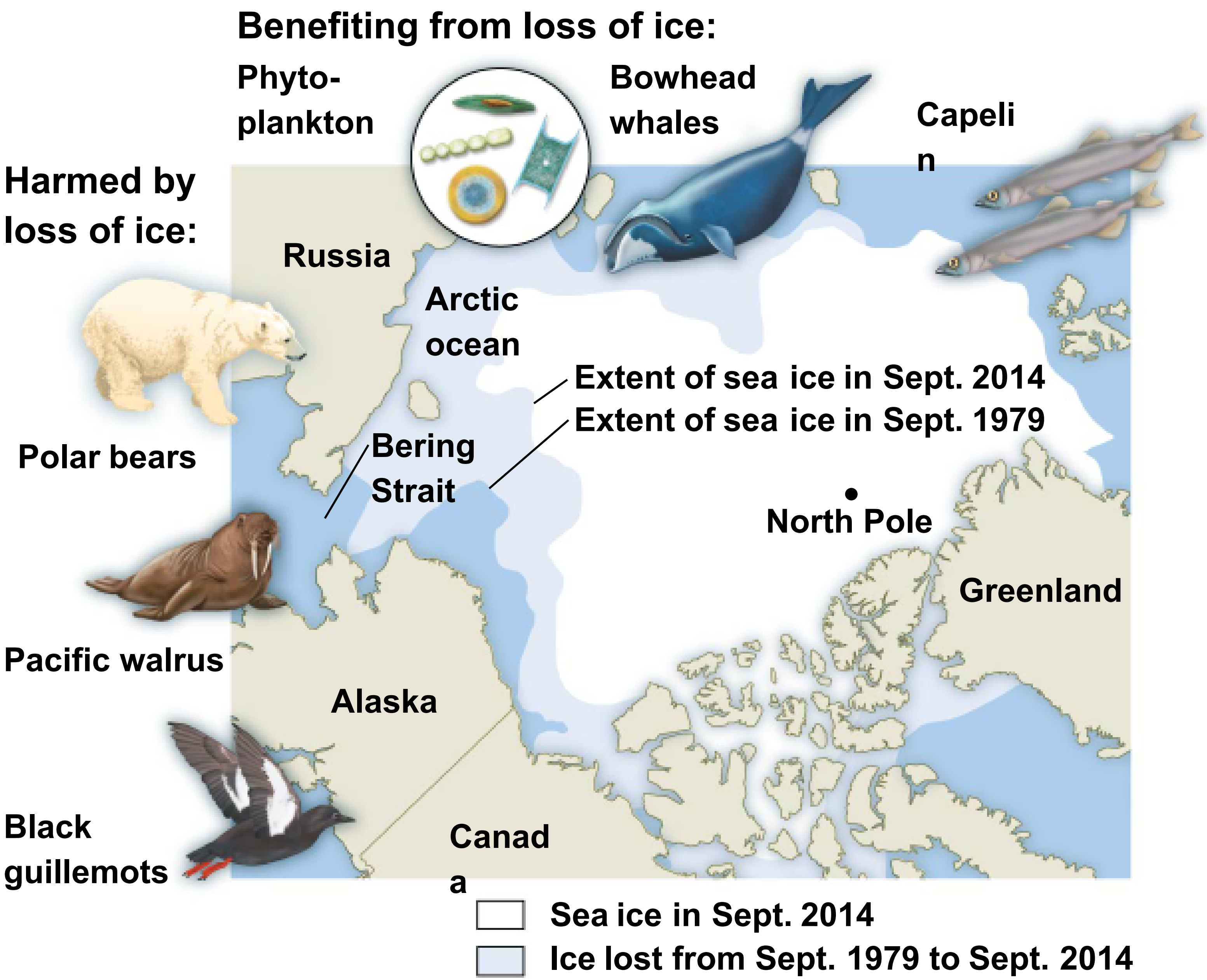


Hydrogen bond
Liquid water:
Hydrogen bonds
break and re-form
Ice:
Hydrogen bonds
are stable

Figure 3.6a

- Many scientists are worried that global warming is having a profound effect on icy environments around the globe
- The rate at which glaciers and Arctic sea ice are disappearing poses an extreme challenge to animals that depend on ice for their survival

Figure 3.7

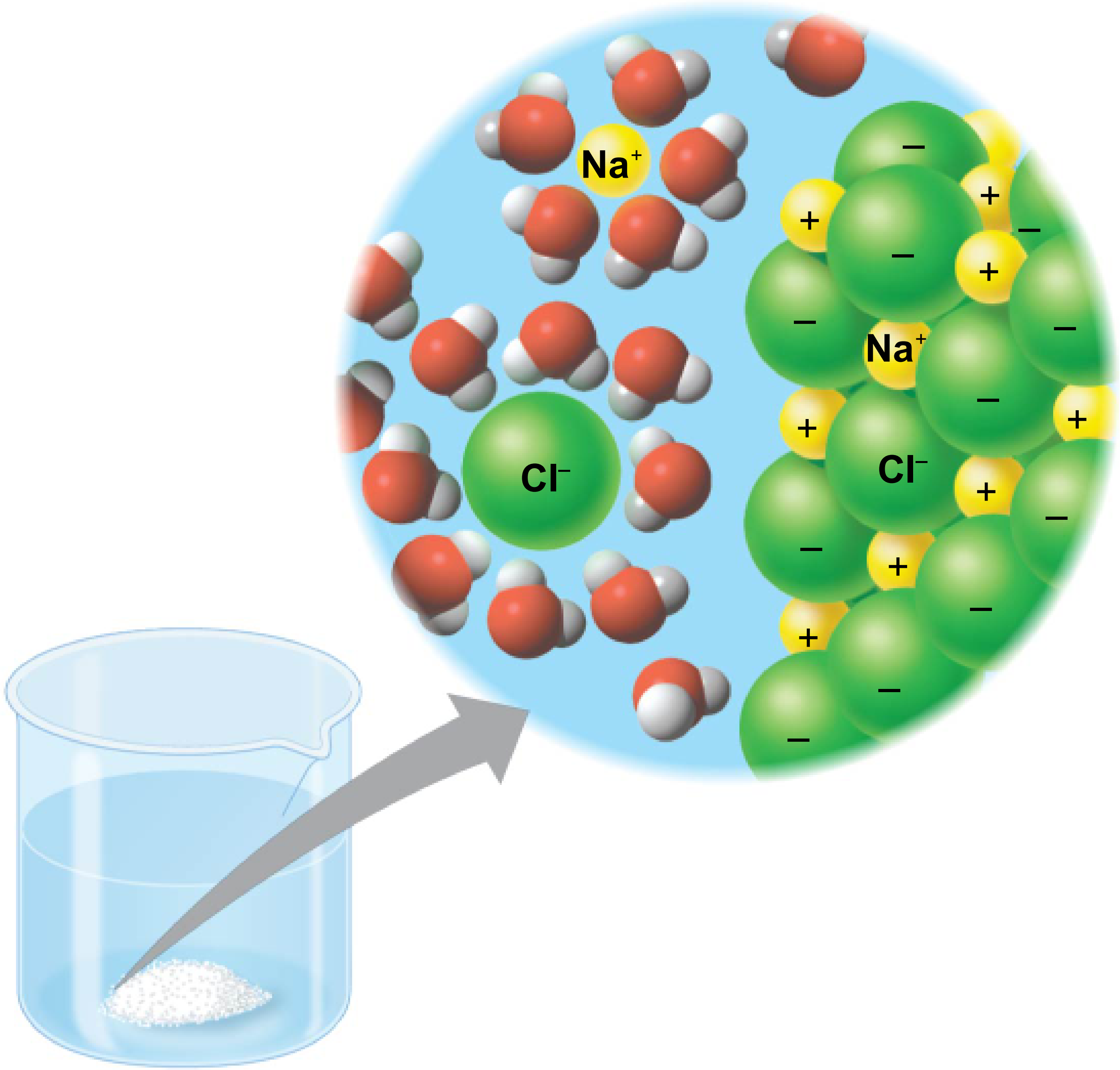


Benefiting from loss of ice:
Phyto-
plankton
Bowhead
whales
Capeli
n
Harmed by
loss of ice:
Russia
Arctic
ocean
Extent of sea ice in Sept. 2014
Extent of sea ice in Sept. 1979
Bering
Strait
North Pole
Greenland
Polar bears
Pacific walrus
Alaska
Black
guillemots
Canad
a
Sea ice in Sept. 2014
Ice lost from Sept. 1979 to Sept. 2014

Water: The Solvent of Life

- 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

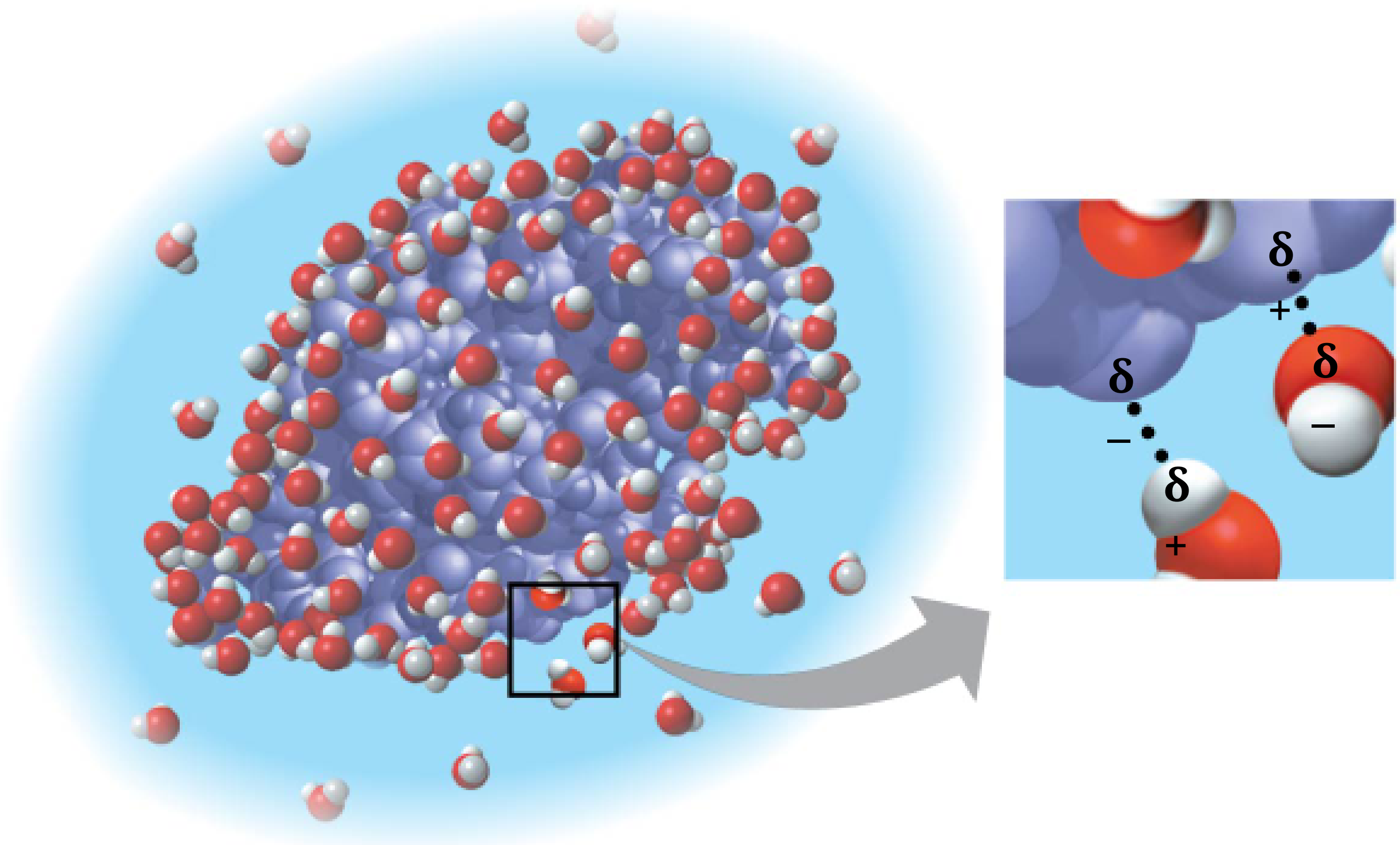
Figure 3.8



- 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

Figure 3.9



Hydrophilic and Hydrophobic Substances

- A **hydrophilic** substance is one that has an affinity for water
- A **hydrophobic** substance is one that does not have an affinity for water
- Oil molecules are hydrophobic because they have relatively nonpolar bonds
- Hydrophobic molecules related to oils are the major ingredients of cell membranes

Solute Concentration in Aqueous Solutions

- Most chemical reactions in organisms involve solutes dissolved in water
- When carrying out experiments, we use mass to calculate the number of solute molecules in an aqueous solution

- **Molecular mass** is the sum of all masses of all atoms in a molecule
- Numbers of molecules are usually measured in moles, where 1 **mole** (**mol**) = 6.02×10^{23} molecules
- Avogadro's number and the unit dalton were defined such that 6.02×10^{23} daltons = 1 g
- **Molarity** (***M***) is the number of moles of solute per liter of solution

Possible Evolution of 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
- In our solar system, Mars has been found to have water

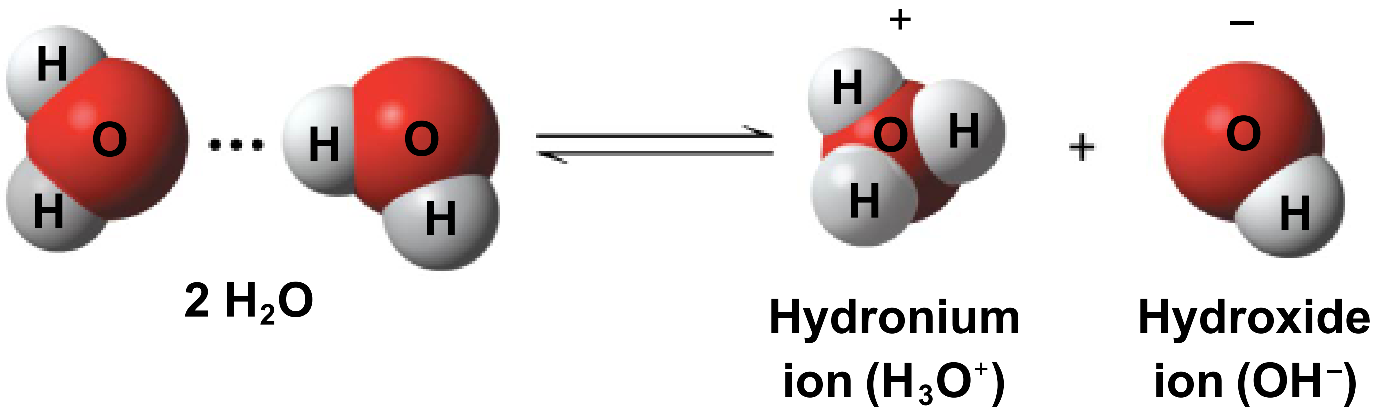
Figure 3.10

Concept 3.3: Acidic and basic conditions affect living organisms

- A hydrogen atom in a hydrogen bond between two water molecules can shift from one to the other
  - The hydrogen atom leaves its electron behind and is transferred as a proton, or **hydrogen ion** (H^+)
  - The molecule that lost the proton is now a **hydroxide ion** (OH^-)
  - The molecule with the extra proton is now a **hydronium ion** (H_3O^+), though it is often represented as H^+

- Water is in a state of dynamic equilibrium in which water molecules dissociate at the same rate at which they are being reformed

Figure 3.UN01



- Though statistically rare, the dissociation of water molecules has a great effect on organisms
- Changes in concentrations of H^+ and OH^- can drastically affect the chemistry of a cell

- Concentrations of H^+ and OH^- are equal in pure water
- Adding certain solutes, called acids and bases, modifies the concentrations of H^+ and OH^-
- Biologists use the pH scale to describe whether a solution is acidic or basic (the opposite of acidic)

Acids and Bases

- An **acid** is a substance that increases the H^+ concentration of a solution
- A **base** is a substance that reduces the H^+ concentration of a solution
- Strong acids and bases dissociate completely in water
- Weak acids and bases reversibly release and accept back hydrogen ions, but can still shift the balance of H^+ and OH^- away from neutrality

The pH Scale

- In any aqueous solution at 25ºC, the product of H^+ and OH^- is constant and can be written as

$$[H^+][OH^-] = 10^{-14}$$

- The **pH** of a solution is defined by the negative logarithm of H^+ concentration, written as

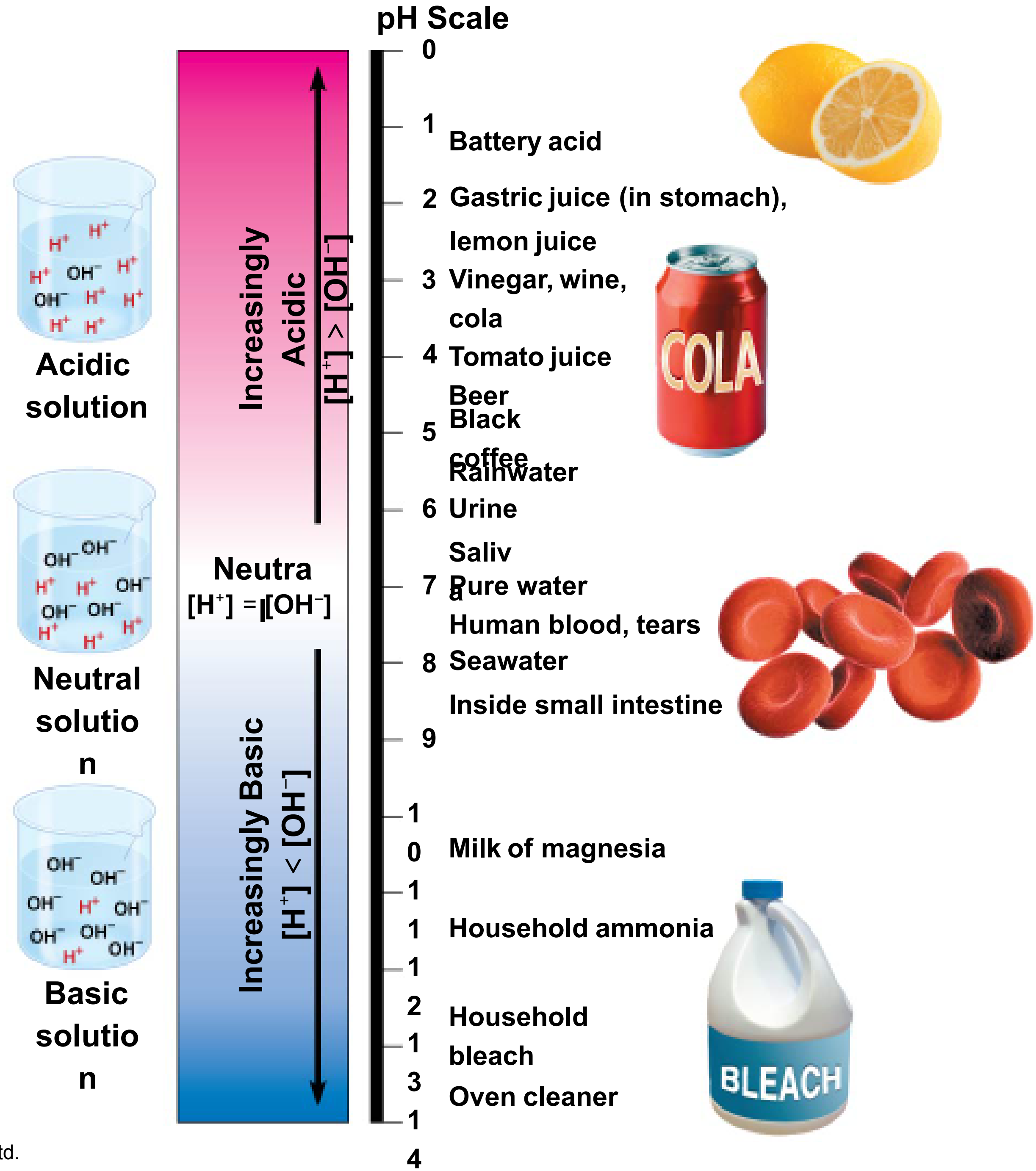
$$pH = -\log [H^+]$$

- For a neutral aqueous solution, $[H^+]$ is 10^{-7}, so

$$pH = -(-7) = 7$$

- Acidic solutions have pH values less than 7
- Basic solutions have pH values greater than 7
- Most biological fluids have pH values in the range of 6 to 8

Figure 3.11


pH Scale
0
1
Battery acid
2
Gastric juice (in stomach),
lemon juice
3
Vinegar, wine,
cola
4
Tomato juice
Beer
Black
coffee
5
Rainwater
6
Urine
Saliv
a
7
Pure water
Human blood, tears
8
Seawater
Inside small intestine
9
1
0
Milk of magnesia
1
1
Household ammonia
1
2
Household
bleach
1
3
Oven cleaner
1
4
COLA
BLEACH
Increasingly
Acidic
[H+] > [OH−]
Neutra
[H+] = [OH−]
Increasingly Basic
[H+] < [OH−]
Acidic
solution
Neutral
solutio
n
Basic
solutio
n
H+
OH−

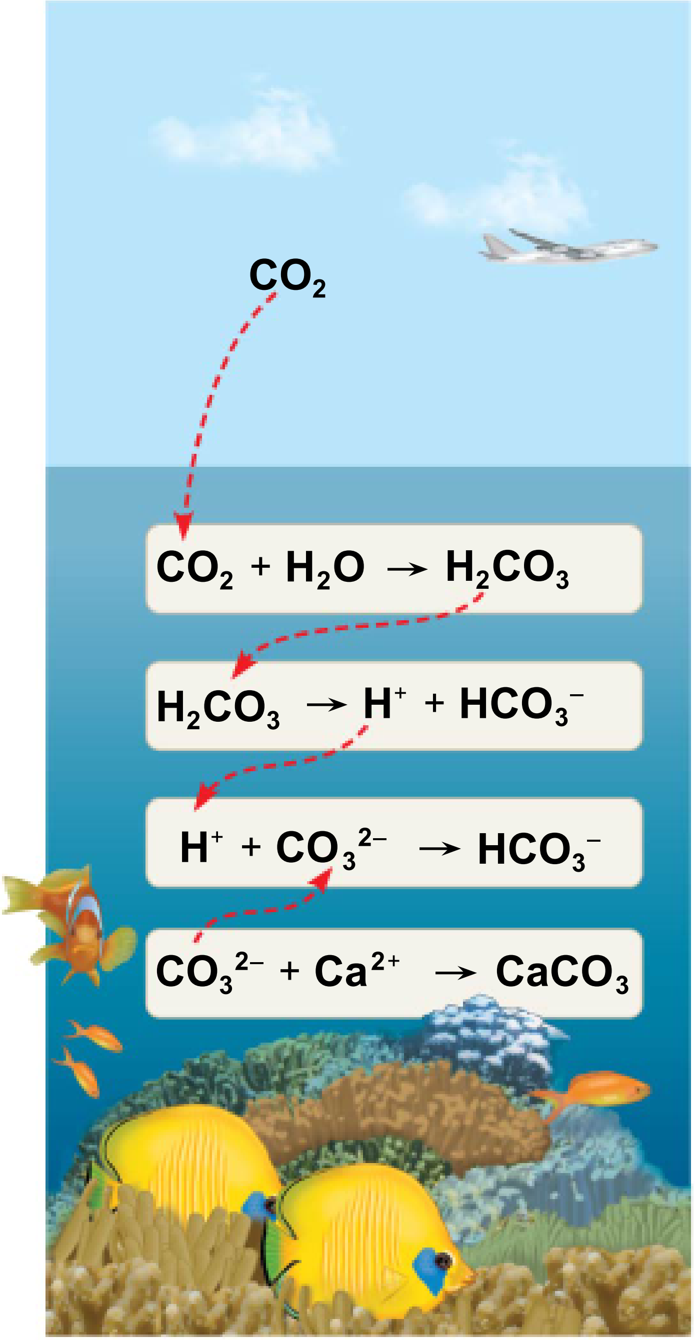
Buffers

- The internal pH of most living cells is close to 7
- **Buffers** are substances that minimize changes in concentrations of H^+ and OH^- in a solution
- Most buffer solutions contain a weak acid and its corresponding base, which combine reversibly with H^+ ions

Acidification: A Threat to Our Oceans

- 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
- CO_2 dissolved in seawater forms carbonic acid; this process is called **ocean acidification**

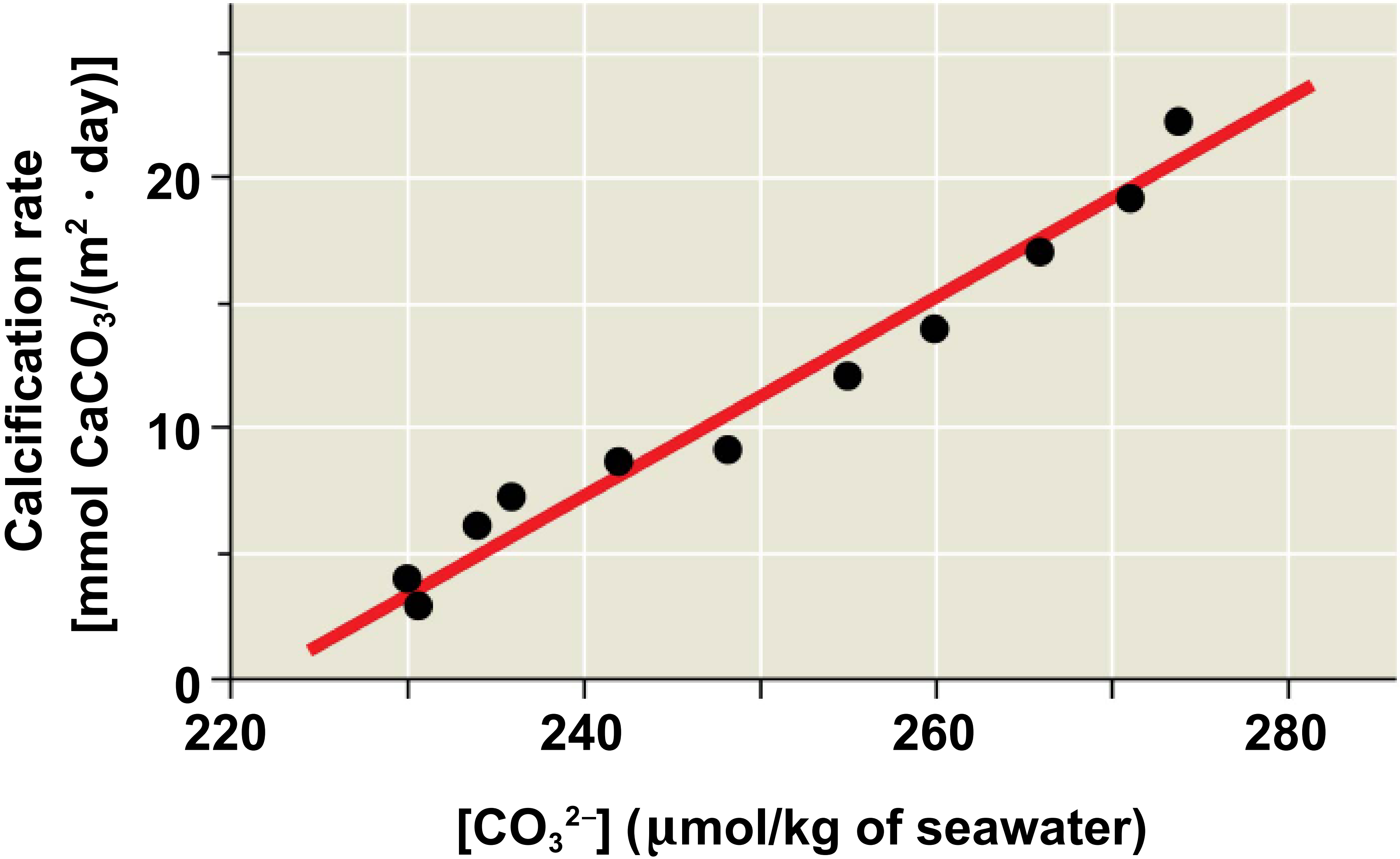
Figure 3.12



CO_2
$CO_2 + H_2O \rightarrow H_2CO_3$
$H_2CO_3 \rightarrow H^+ + HCO_3^-$
$H^+ + CO_3^{2-} \rightarrow HCO_3^-$
$CO_3^{2-} + Ca^{2+} \rightarrow CaCO_3$

- As seawater acidifies, H^+ ions combine with carbonate ions to produce bicarbonate
- Carbonate is required for calcification (production of calcium carbonate) by many marine organisms, including reef-building corals
- We have made progress in learning about the delicate chemical balances in oceans, lakes, and rivers

Figure 3.UN02a



Data from C. Langdon et al., Effect of calcium carbonate saturation state on the calcification rate of an experimental coral reef, *Global Biogeochemical Cycles* 14:639–654 (2000).

Figure 3.UN02b

Figure 3.UN03

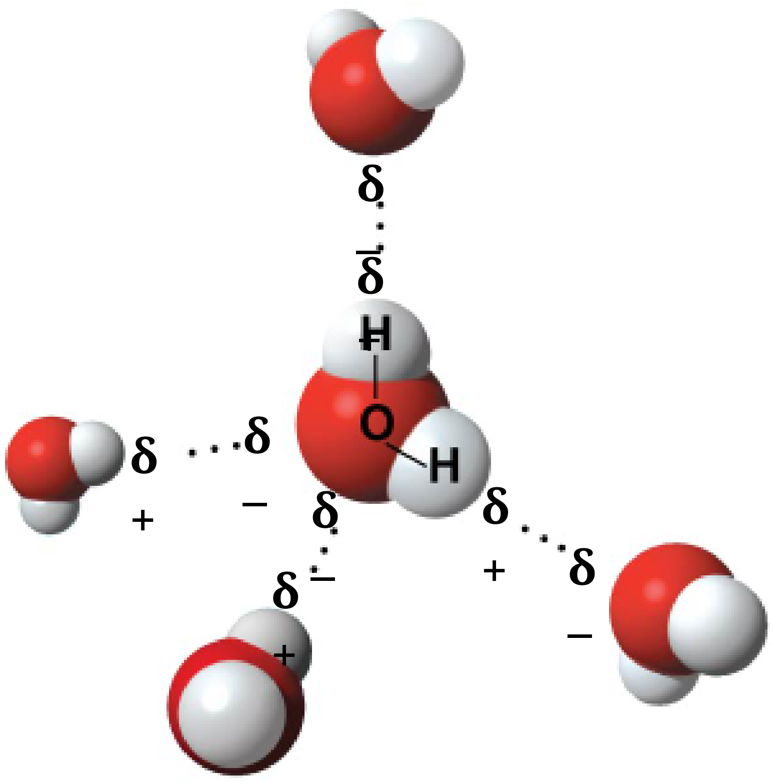


Figure 3.UN04

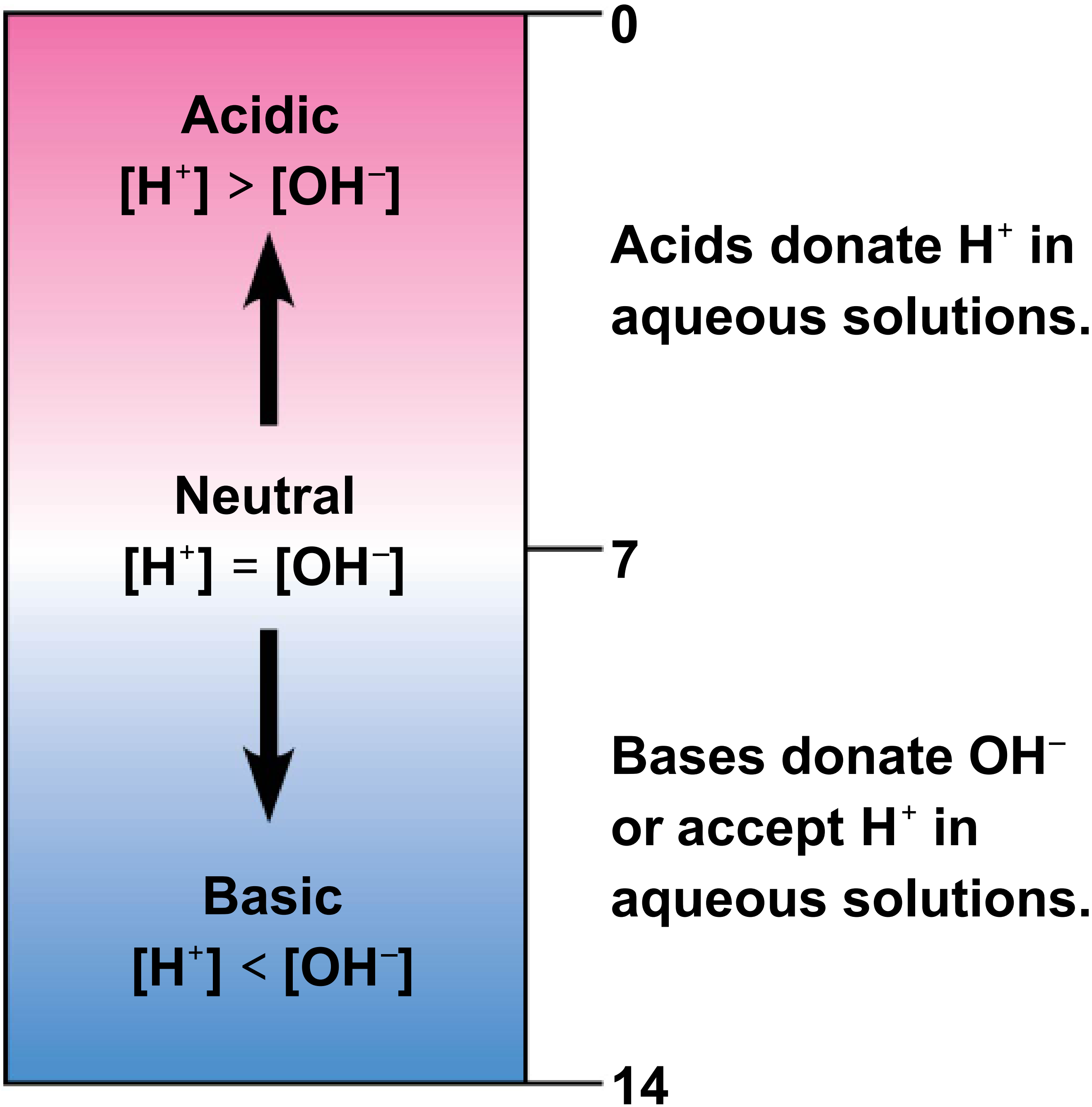


Figure 3.UN05