Ch. 2 The Chemistry of Life

Why are we studying chemistry?

_Chemistry is the foundation of Biology_
- Everything is made of matter
- Matter is made of atoms

**Hydrogen**
- 1 proton
- 1 electron

**Oxygen**
- 8 protons
- 8 neutrons
- 8 electrons

**Proton** + **Neutron** 0 **Electron** –
Life requires ~25 chemical elements

• About 25 elements are essential for life
  – Four elements make up 96% of living matter:
    • carbon (C)  • hydrogen (H)
    • oxygen (O)  • nitrogen (N)
  – Four elements make up most of remaining 4%:
    • phosphorus (P)  • calcium (Ca)
    • sulfur (S)  • potassium (K)
Bonding properties

• Effect of electrons
  – electrons determine chemical behavior of atom
  – depends on number of electrons in atom’s outermost shell
    • valence shell

How does this atom behave?
Bonding properties

• Effect of electrons
  – chemical behavior of an atom depends on number of electrons in its valence shell

What’s the magic number? How does this atom behave? How does this atom behave?
Elements & their valence shells

- Elements in the **same row** have the same **number of shells**

Moving from left to right, each element has a sequential addition of electrons (& protons)
Elements & their valence shells

Elements in the same **column** have the **same valence** & similar chemical properties

Remember some food chains are built on reducing O to $\text{H}_2\text{O}$ & some on reducing S to $\text{H}_2\text{S}$.
Chemical reactivity

- Atoms tend to
  - complete a partially filled valence shell
  or
  - empty a partially filled valence shell

This tendency drives chemical reactions...

and creates bonds
Bonds in Biology

• **Weak bonds**
  – hydrogen bonds
    • attraction between + and –
  – hydrophobic & hydrophilic interactions
    • interaction with H₂O
  – van derWaals forces
  – (ionic)

• **Strong bonds**
  – covalent bonds
Covalent bonds

• Why are covalent bonds strong bonds?
  – two atoms share a pair of electrons
  – both atoms holding onto the electrons
  – very stable

• Forms molecules

H₂ (hydrogen gas)

H₂O (water)
Multiple covalent bonds

- 2 atoms can share >1 pair of electrons
  - double bonds
    - 2 pairs of electrons
  - triple bonds
    - 3 pairs of electrons

- **Very strong bonds**

  More is better!
Nonpolar covalent bond

• Pair of electrons **shared equally** by 2 atoms
  – **example**: hydrocarbons = C\(_x\)H\(_x\)
  • methane (CH\(_4\) )

balanced, stable, good building block
Polar covalent bonds

• Pair of electrons **shared unequally** by 2 atoms
  – **example**: water = H₂O
  • oxygen has stronger “attraction” for the electrons than hydrogen
  • oxygen has higher electronegativity
  • water is a **polar molecule**
    – + vs – poles
    – leads to many interesting properties of water...
Hydrogen bonding

• Polar water creates molecular attractions
  – attraction between positive H in one H$_2$O molecule to negative O in another H$_2$O
  – also can occur wherever an -OH exists in a larger molecule

• Weak bond
Why are we studying water?

All life occurs in water
- inside & outside the cell
Chemistry of water

- $\text{H}_2\text{O}$ molecules form H-bonds with each other
  - $+\text{H}$ attracted to $-\text{O}$
  - creates a **sticky molecule**
Elixir of Life

• Special properties of water
  1. **cohesion & adhesion**
     • surface tension, capillary action
  2. **good solvent**
     • many molecules dissolve in H\(_2\)O
     • hydrophilic vs. hydrophobic
  3. **lower density as a solid**
     • ice floats!
  4. **high specific heat**
     • water stores heat
  5. **high heat of vaporization**
     • heats & cools slowly

Ice! I could use more ice!
1. Cohesion & Adhesion

- **Cohesion**
  - H bonding between H$_2$O molecules
  - water is “sticky”
    - surface tension
    - drinking straw

- **Adhesion**
  - H bonding between H$_2$O & other substances
    - capillary action
    - meniscus
    - water climbs up paper towel or cloth

Try that with flour... or sugar...
How does $\text{H}_2\text{O}$ get to top of trees?

Transpiration is built on cohesion & adhesion

Let's go to the videotape!
2. Water is the solvent of life

- Polarity makes H$_2$O a good **solvent**
  - polar H$_2$O molecules surround + & – ions
  - solvents dissolve solutes creating solutions
What dissolves in water?

- **Hydrophilic**
  - substances have attraction to $\text{H}_2\text{O}$
  - **polar** or **non-polar**?
Water Potential
Plant Cells in Pure Water

Pure water (a hypotonic solution) will initially move into the cells.

After a period of time the cells will become turgid.

As turgor pressure increases water will diffuse out of the cell... eventually equilibrium will be reached.
Water Potential is...

...a measure of the energy available for reaction or movement.
- measures the ability of water to move.
- water always moves from areas of high potential to areas of low water potential.

- The symbol for water potential is the Greek letter $\Psi$. 

$\Psi$
Water Potential

Two components:

- **Osmotic potential** (due to solutes)
- **Pressure potential** (due to turgor pressure).

These two pressures have opposite effects on water movement.

As one rises, the other decreases...
Water potential is just the sum of the pressure and osmotic components.

\[ \psi = \psi_p + \psi_\pi \]

Pure water has \( \psi_\pi \) of 0

\( \psi_\pi \) is \textit{negative} for all solutions

Pure water always flows to the lower potential, so, \( \psi_\pi \) must be \textit{negative} (lower than zero) for any water containing solutes.
Water under pressure (high P)
• few solutes (low $\pi$, *not* very negative $\psi_\pi$).

Water will flow from the cell to the solution, from high (nearly zero) potential to low (very negative) potential.

Fresh water flows to salt…
The rivers flow to the sea…

Water at low pressure (low P)
• lots of solutes
• high $\pi$
• very negative $\psi_\pi$
Some Basic Principles

• Water always moves from high water potential to low water potential.
• Water potential is a measure of the tendency of water to move from high free energy to lower free energy.
• Distilled water in an open beaker has a water potential of 0(zero).
• The addition of solute decreases water potential.
• The addition of pressure increases water potential.
• In cells, water moves by osmosis to areas where water potential is lower.
  • A hypertonic solution has lower water potential.
  • A hypotonic solution has higher water potential.
What doesn’t dissolve in water?

- **Hydrophobic**
  - substances that don’t have an attraction to $\text{H}_2\text{O}$
  - **polar** or **non-polar**?

fat (triglycerol)

Oh, look hydrocarbons!
3. The special case of ice

• Most (all?) substances are more dense when they are solid, but **not** water...

• **Ice floats!**
  – H bonds form a crystal

And this has made all the difference!
Ice floats

Ice
Hydrogen bonds are stable

Liquid water
Hydrogen bonds constantly break and re-form
Why is “ice floats” important?

• Oceans & lakes don’t freeze solid
  – **surface ice insulates water below**
    • allowing life to survive the winter
  – if ice sank...
    • ponds, lakes & even oceans would freeze solid
    • in summer, only upper few inches would thaw
  – **seasonal turnover of lakes**
    • **sinking cold H_{2}O cycles nutrients in autumn**
4. Specific heat

- $\text{H}_2\text{O}$ resists changes in temperature
  - high specific heat
  - takes a lot to heat it up
  - takes a lot to cool it down

- $\text{H}_2\text{O}$ moderates temperatures on Earth
5. Heat of vaporization

Organisms rely on heat of vaporization to remove body heat.

Evaporative cooling
Ionization of water & pH

• Water ionizes
  – $H^+$ splits off from $H_2O$, leaving $OH^-$
    • if $[H^+] = [\cdot OH]$, water is **neutral**
    • if $[H^+] > [\cdot OH]$, water is **acidic**
    • if $[H^+] < [\cdot OH]$, water is **basic**

• **pH scale**
  – how acid or basic solution is
  – $1 \rightarrow 7 \rightarrow 14$

$H_2O \rightarrow H^+ + OH^-$
<table>
<thead>
<tr>
<th>H⁺ Ion Concentration</th>
<th>pH</th>
<th>Solutions</th>
<th>OH⁻ Ion Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>10⁻¹⁰</td>
<td>10</td>
<td>Hydrochloric acid</td>
<td>10⁻¹³</td>
</tr>
<tr>
<td>10⁻⁹</td>
<td>9</td>
<td>Stomach acid Lemon juice</td>
<td>10⁻¹²</td>
</tr>
<tr>
<td>10⁻⁸</td>
<td>8</td>
<td>Vinegar, cola, beer</td>
<td>10⁻¹¹</td>
</tr>
<tr>
<td>10⁻⁷</td>
<td>7</td>
<td>Tomatoes</td>
<td>10⁻¹⁰</td>
</tr>
<tr>
<td>10⁻⁶</td>
<td>6</td>
<td>Black coffee, Rainwater</td>
<td>10⁻⁹</td>
</tr>
<tr>
<td>10⁻⁵</td>
<td>5</td>
<td>Urine, Saliva</td>
<td>10⁻⁸</td>
</tr>
<tr>
<td>10⁻⁴</td>
<td>4</td>
<td>Pure water, Blood</td>
<td>10⁻⁷</td>
</tr>
<tr>
<td>10⁻³</td>
<td>3</td>
<td>Seawater</td>
<td>10⁻⁶</td>
</tr>
<tr>
<td>10⁻²</td>
<td>2</td>
<td>Baking soda</td>
<td>10⁻⁵</td>
</tr>
<tr>
<td>10⁻¹</td>
<td>1</td>
<td>Great Salt Lake</td>
<td>10⁻⁴</td>
</tr>
<tr>
<td>10⁰</td>
<td>0</td>
<td>Household ammonia</td>
<td>10⁻³</td>
</tr>
<tr>
<td>10¹</td>
<td></td>
<td>Household bleach</td>
<td>10⁻²</td>
</tr>
<tr>
<td>10²</td>
<td></td>
<td>Oven cleaner</td>
<td>10⁻¹</td>
</tr>
<tr>
<td>10³</td>
<td></td>
<td>Sodium hydroxide</td>
<td>10⁰</td>
</tr>
</tbody>
</table>

**tenfold change in H⁺ ions**

pH1 → pH2 10⁻¹ → 10⁻²
10 times less H⁺

pH8 → pH7 10⁻⁸ → 10⁻⁷
10 times more H⁺

pH10 → pH8 10⁻¹⁰ → 10⁻⁸
100 times more H⁺
Buffers & cellular regulation

- pH of cells must be kept ~7
  - pH affects shape of molecules
  - shape of molecules affect function
  - pH affects cellular function

- Control pH by **buffers**
  - reservoir of $H^+$
    - donate $H^+$ when $[H^+]$ falls
    - absorb $H^+$ when $[H^+]$ rises
The Mammalian Body Regulates pH in Several Ways

• Human blood pH is 7.4

• Blood pH above 7.4 = alkalosis

• Blood pH below 7.4 = acidosis

• Human body must get rid of ~15 moles potential acid/day (mostly CO$_2$)

• Buffers (such as bicarbonate and CO$_2$) minimize pH change

• CO$_2$ is eliminated by the lungs

• Other acids and bases are eliminated by the kidneys
The Chief Mammalian Blood Buffer is a Mixture of Bicarbonate and Carbon Dioxide

• All body fluids, inside or outside cells have buffers which defend the body against pH changes

• The most important buffer in extracellular fluids, including blood, is a mixture of carbon dioxide ($CO_2$) and bicarbonate ion ($HCO_3^-$)

• $CO_2$ forms carbonic acid ($H_2CO_3$) when dissolved in water. It acts as an acid, donating hydrogen ions when pH rises too high.

• $CO_2$ acts as a base, soaking up hydrogen ions when pH drops too low.

• There are also other buffers in blood, such as proteins and phosphate, but they are less important

• Blood pH is determined by a balance between bicarbonate and $CO_2$
The equilibrium equation for carbon dioxide acting as a buffer in the blood is provided below:

\[ H^+ + HCO_3^- \rightleftharpoons H_2CO_3 \rightleftharpoons H_2O + CO_2 \]
Too little $\text{HCO}_3^−$ or too much $\text{CO}_2$ – Acidosis

pH lowers because $\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{CO}_3$, making carbonic acid. $\text{HCO}_3^−$ levels are too low to compensate by bonding to the $\text{H}^+$ released. Increasing $\text{H}^+$ ions denature proteins and enzymes.

• $\text{CO}_2$ can be raised by hypoventilation from pneumonia, emphysema, or metabolic conditions such as ketoacidosis caused by excess fat metabolism (diabetes mellitus) will lower bicarbonate.
Too Much $CO_2$ or Too Little $HCO_3^-$ Will Cause **Acidosis**

- The balance will swing toward a low pH, producing acidosis, if $CO_2$ is raised or $HCO_3^-$ lowered.

- $CO_2$ can be raised by hypoventilation (pneumonia, emphysema).

- Metabolic conditions such as **ketoacidosis** caused by excess fat metabolism (**diabetes mellitus**) will lower bicarbonate.
Too much HCO$_3^-$ or too little CO$_2$ – **Alkalosis**

pH increases because HCO$_3^-$ removes the H+

Causes include hyperventilation and vomiting.

**Exercise** along with normal breathing will increase CO$_2$ blood levels, restoring pH to normality.
Too Much HCO$_3^-$ or Too Little CO$_2$ Will Cause Alkalosis

• The balance will swing the other way, producing alkalosis, if CO$_2$ is lowered or HCO$_3^-$ raised.

• CO$_2$ can be lowered by **hyperventilation**.

• Vomiting removes stomach acid and raises bicarbonate.

• **Alkalosis** is less common than acidosis.
Figure 1
This figure highlights some of the major acute (short-term) effects on the body during exercise.

Changes in blood:
- O$_2$ used up
- CO$_2$ produced
- H$^+$ produced
- Lactic acid produced
- Temperature increased
- pH lowered

Other effects:
- Breathing rate increased
- Heart rate increased

http://www.chemistry.wustl.edu/~edudev/LabTutorials/Buffer/Buffer.html
Figure 3
• This figure shows the major organs that help control the blood concentrations of CO$_2$ and HCO$_3^-$, and thus help control the pH of the blood.

• Removing CO$_2$ from the blood helps increase the pH.

• Removing HCO$_3^-$ from the blood helps lower the pH.

http://www.chemistry.wustl.edu/~edudev/LabTutorials/Buffer/Buffer.html
Blood pH is Chiefly Regulated by the Lungs and Kidneys in Mammals

- Normal metabolism produces large amounts of CO$_2$ continuously (about 14 moles/day)
- If this CO$_2$ were not removed we would rapidly develop fatal acidosis
- Almost all of the CO$_2$ is removed from the lungs
- If blood pH is low, respiration is stimulated so that more CO$_2$ is removed, raising the pH to the normal level
- Bicarbonate is adjusted in the kidney
- The kidneys can generate new HCO$_3^-$ when it is low