Life, the Universe, and Everything

The universe is composed of energy and matter.

$E=mc^2$

- At the beginning of the universe, energy was converted into matter. Big Bang!
- Only in rare circumstances, like inside stars and atomic blasts, matter is converted back into energy.

•Energy is often converted from one form into another:
(e.g., light energy into chemical energy; chemical enegy into kinetic energy; kinetic energy into heat energy; etc.)
but it is neither created nor destroyed.

•But matter, with rare exceptions, stays the same type of matter.

Matter is in the form of chemicals.

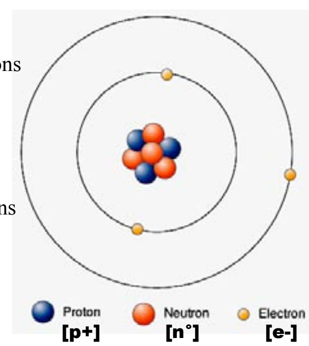
- Chemicals are constructed from atoms.
- Different types of matter, i.e., different elements, have different atoms.

The **Atom**

- A single unit of matter
- Composed of three types of subatomic particles
  - Neutrons (n^o): mass = 1 atomic mass unit; no electrical charge (neutral)
  - Protons (p^+): mass = 1 atomic mass unit; positive electrical charge (+1)
  - Electrons (e^-): mass is trivial; negative electrical charge (–1)

Atomic Structure

- Neutrons and protons form the nucleus
- **Atomic Mass (Atomic Weight)** = number of protons and neutrons combined
- Electrons orbit around the nucleus



Atomic Number

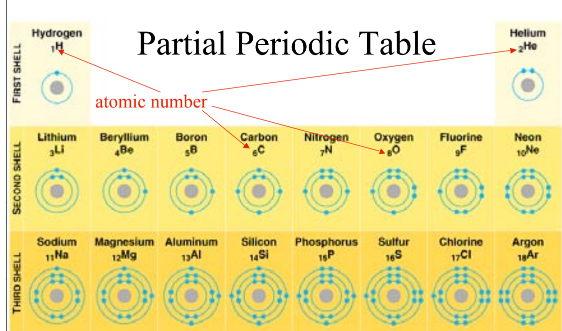
- A chemical reaction is the interaction of electrons from different atoms.
- The number, distribution and activity of electrons around an atom's nucleus is determined by the number of protons in that nucleus.

∴ The "chemical identity" (type of element) for any atom is determined by the number of protons in its nucleus!

# of p⁺ = the **Atomic Number** for that atom.

E.g.: Any atom that has **6 p⁺** in its nucleus (atomic number = 6) is defined as **carbon**, no matter how many e⁻ or n° it has!

Partial Periodic Table



96% of body mass is composed of four different elements

- **O**xygen (65%)
- **C**arbon (18%)
- **H**ydrogen (10%)
- **N**itrogen (3%)

Remember: 65-75% of total body weight is H_20

Table 2.1

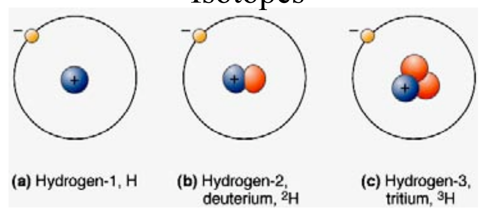
NATURALLY OCCURRING ELEMENTS IN THE HUMAN BODY

Symbol	Element	Wet Weight Percentage*	
O	Oxygen	65.0	96.3
C	Carbon	18.5	
H	Hydrogen	9.5	
N	Nitrogen	3.3	
Ca	Calcium	1.5	
P	Phosphorus	1.0	
K	Potassium	0.4	
S	Sulfur	0.3	
Na	Sodium	0.2	
Cl	Chlorine	0.2	
Mg	Magnesium	0.1	

Trace elements (less than 0.01%): 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), and zinc (Zn).

*Includes water.

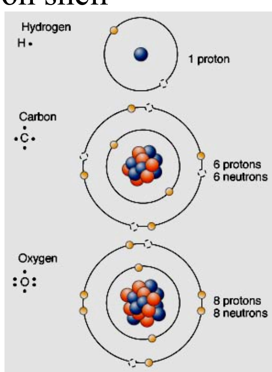
Isotopes



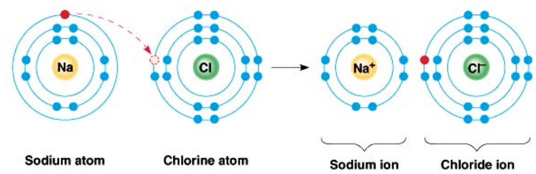
- Atoms of the same element (i.e., same atomic number) but with differing numbers of neutrons, have the same chemical identity but different atomic weights.
- These variations of an element are called **isotope**s.
- Some isotopes are unstable and emit radioactive energy. Such isotopes are **radioisotopes**.

Electron shell

- Electrons have different levels of energy
- Each energy level is called an electron shell
- Outer shell called **valence shell**
- Only valence shell electrons participate in chemical reactions

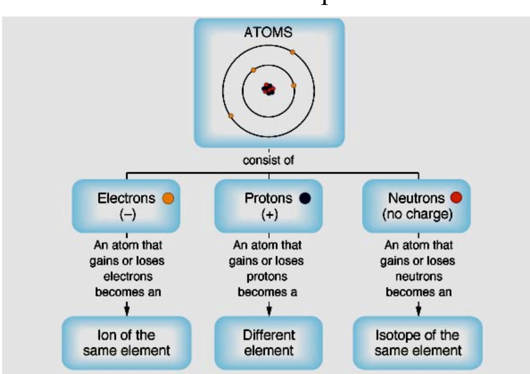


Ions

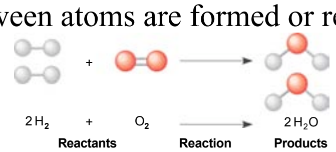


- If # p^+ = # e^-: neutral atom
- If # $p^+ \neq$ # e^-: charged atom = **ion**
- If the valence shell loses an electron = positive ion (**cation**).
- If the valence shell gains an electron = negative ion (**anion**).

Ions & Isotopes



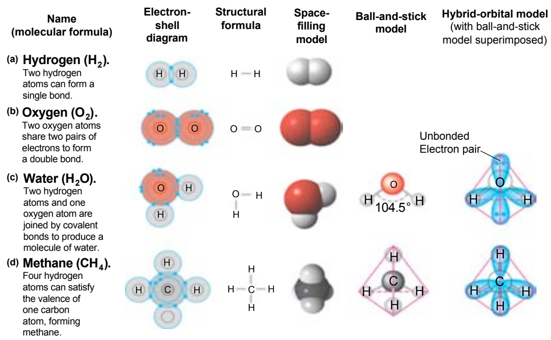
Chemical reactions occur when bonds between atoms are formed or rearranged



- Molecule: two or more atoms bonded together
  - Compound: molecule constructed of more than one ***kind*** of atom.

  E.g.: H_2 and O_2 and H_2O are all ***molecules***.
  - But H_2 and O_2 are *elemental* molecules.
  - And H_2O is a ***compound*** molecule.

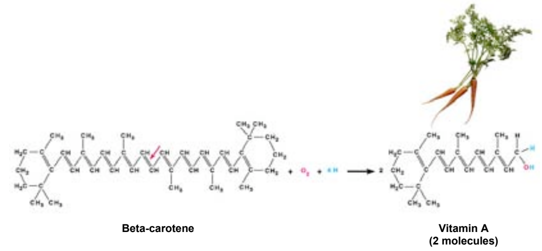
Molecules can be represented in many ways



Tables 2.11 & 2.16

Living cells carry out millions of chemical reactions that rearrange matter in significant ways

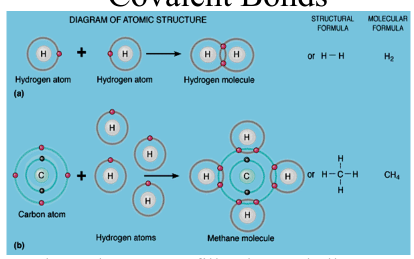
- Biological molecules have many atoms bound precisely in complex forms.
- How does the right rearrangement of the right bond at the right time happen?



Types of Chemical Bonds

- Covalent Bonds
- Ionic Bonds
- Hydrogen Bonds

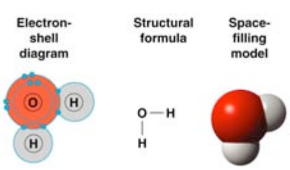
Covalent Bonds

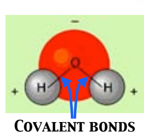


- Atoms share electrons to fill valence shell
- Electrons are shared in pairs
- Each pair forms one bond

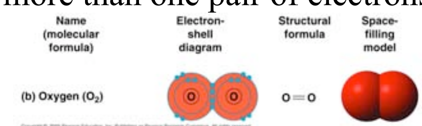
Example: Water (H_2O)

- Oxygen: 6 valence e^-
  - Needs 2 e^- to fill shell
  - Gets 1 e^- from each hydrogen atom
- Hydrogen: 1 valence e^-
  - Each needs 1 e^- to fill shell
  - Each gets 1 e^- from oxygen

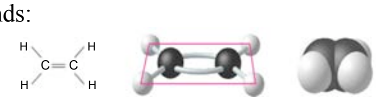




Two atoms can share more than one pair of electrons



- Double bonds:
  O=O
  C=C
- Triple bonds:
  N≡N

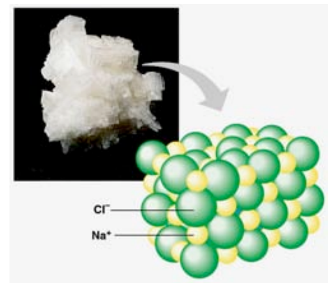


Ionic Bonds

- Based on electromagnetic attraction between ions of opposite charge
- Ions: charged atoms
  - Loss of e^-: positive charge on atom
  - Gain of e^-: negative charge on atom
- **Salts**: two ions of opposite charge bonded together

Ionic bond between Na^+ and Cl^- form NaCl, table salt

- Regular stacking of atoms cause salts to form crystals in absence of water

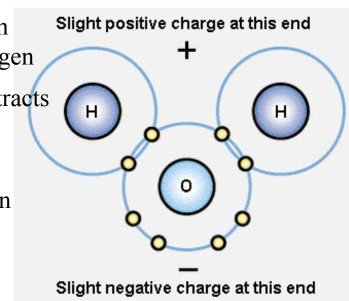


Ions separate in presence of water

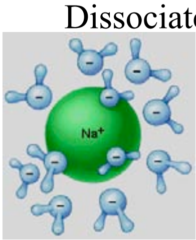
- **Dissociation**: breaking of ionic bond
- **Dissolve:** surrounding a molecule like NaCl with H_2O
- Why? Because water is a polar molecule.

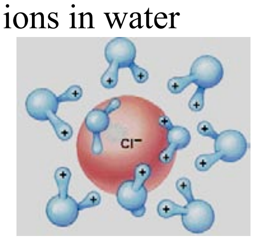
Water is a polar molecule

- Nucleus of oxygen bigger than hydrogen
- Bigger nucleus attracts e^- better
- Distribution of electrons is uneven around molecule



Dissociated ions in water

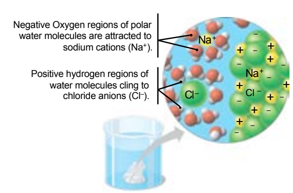




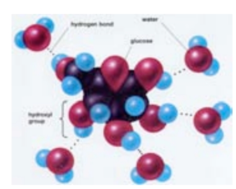
Na^+ surrounded by oxygen side of H_2O

Cl^- surrounded by hydrogen side of H_2O

Water is a versatile solvent



Salt ions dissolving in water



Glucose dissolved in water

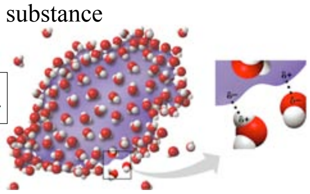
- **Solutes** whose charges or polarity allow them to stick to water molecules dissolve in water
  - they form aqueous solutions

Aqueous Solutions

Polar or ionic molecule dissolved in water forms a solution

- **Solution**: solutes dissolved by a solvent
- **Solvent** = water
- **Solutes** = dissolved substance

A protein solution = protein dissolved in water

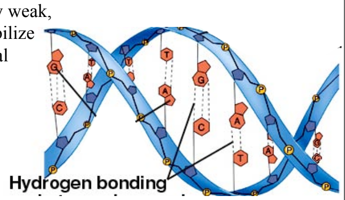


Water: the "universal solvent"

- Many substances dissolve in water
- Examples of water soluble substances:
  - Salts (ions, or electrolytes)
  - Sugars and other nutrients
  - Vitamins
  - Hormones

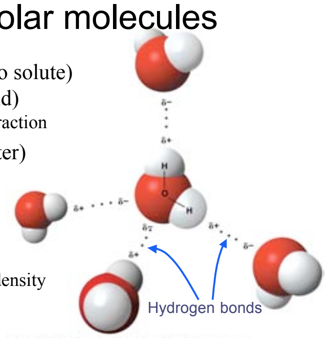
Hydrogen bonds form between partial (∂) charges

- Both intermolecular and intramolecular
  - **H** of amino & alcohol side groups are ∂+
  - **=O** of carbonyl groups are ∂–
- Individual H-bond is very weak, but many combine to stabilize 3-D structure of biological macromolecules
  - Important for protein shape, DNA, etc.



Many of water's unique properties relate to hydrogen bonds formed among these small polar molecules

- Solvent power (water to solute)
- Cohesion (water to solid)
  - Wetting & capillary attraction
- Adhesion (water to water)
  - Surface tension & column tension
  - High heat capacity & heat of vaporization
  - Liquid density > solid density



Dissociation of Water

- 1 out of 500,000,000 water molecules ionizes:

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

Hydrogen ion (= 1 p⁺) Hydroxide ion

- = 6×10^{16} per liter of water = 10^{-7} moles per liter
- Hence, neutral water contains:

  $10^{-7} M\ H^+ + 10^{-7} M\ OH^-$
- And $[H^+] = [OH^-]$
- $pH = -\log [H^+] = -\log (10^{-7} M) = \mathbf{7}$

Acids & Bases

- So, in a **neutral** solution, $[H^+] = [OH^-]$; **pH = 7.00**
- An **Acid** is a compound that **adds** extra H^+ to the solution. I.e., "**H^+ donor**"
- Thus, an **acidic** solution has $[H^+] > [OH^-]$ **pH < 7** (0.00–6.99)
- A **Base** is a compound that **removes** H^+ from the solution. I.e., "**H^+ acceptor**"
- Thus, an **basic** (alkaline) solution has $[H^+] < [OH^-]$ **pH > 7** (7.01–14.00)
- ↓pH = ↑acidity & ↑pH = ↓acidity

(Note: normal blood pH is 7.35–7.45 — slightly basic!)

Effects of pH on Bioactivity

- Relative amount of H^+ in solution (i.e., the pH) can alter the charge and polarity of other solutes.
- ➥ Δ ionic or hydrogen bonds ➟ Δ folding & 3-dimensional shape of large organic solutes (esp. proteins)
- ➥ Δ 3-dimensional shape ➟ Δ biological activity of those organic molecules.
- ➥ even small ΔpH can have major impacts on biological activity.

Buffers

- System of molecules and ions that act to prevent changes in $[H^+]$. ➟ Stabilizes pH of a solution.
- Blood bicarbonate buffer system:

  $H_20 + C0_2 \Leftrightarrow H_2C0_3 \Leftrightarrow H^+ + HC0_3^-$ (bicarbonate ion)

  - Reaction can proceed in either direction depending upon the concentration of molecules and ions.
  - Thus if ↑H^+: $HC0_3^- + H^+ \rightarrow H_2C0_3 \rightarrow H_20 + C0_2$ ➟ ↓H^+
  - But if ↓H^+: $H_20 + C0_2 \rightarrow H_2C0_3 \rightarrow H^+ + HC0_3^-$ ➟ ↑H^+
- Thereby maintaining normal blood pH range of 7.35 – 7.45
  - Acidosis: blood pH < 7.35 (Note: ***not*** acidic!)
  - Alkalosis: blood pH > 7.45

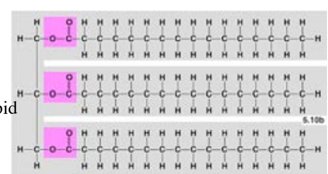
Biological Molecules

Some molecules are special in biology

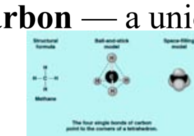
- H_2O - small, slightly polar molecule → "universal solvent"
- Organic molecules are based on **carbon**.

H
H– C –H
H
methane

lipid

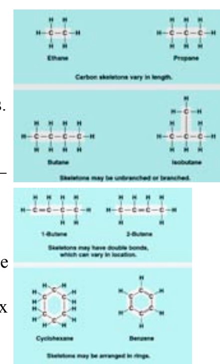


Carbon — a unique element



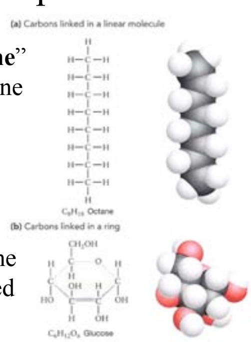
1. Each carbon atom forms four bonds.
2. Carbon atoms can bond to other carbons, thus constructing long and/or branched chains of carbon — the "carbon backbone" of the molecule.
3. Carbon can form double bonds to modify the shape or flexibility of the chains.

Thus ***only carbon*** can form the complex molecules needed for complex biological functions.



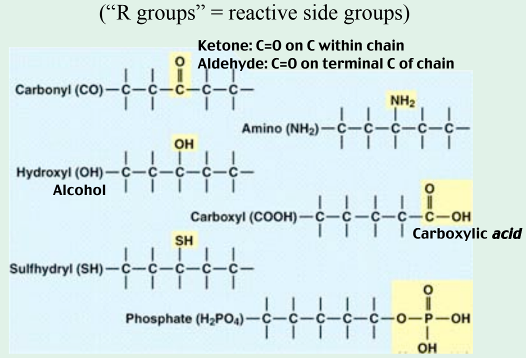
Organic Compounds

- Have a "**carbon backbone**" — a chain of more than one carbon.
- "**Organic**" originally meant "made by **organisms**."
  - (Most still are. But some are synthetically derived from those that are.)



Functional Groups of Organic Molecules

("R groups" = reactive side groups)



- C.f., Fig. 4.10

Organic Macromolecules

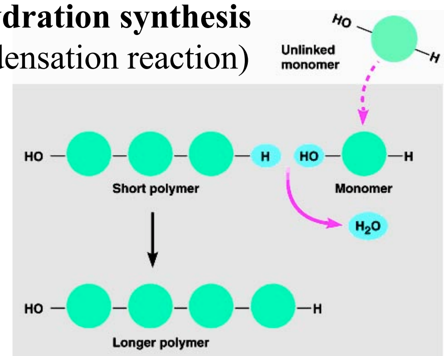
Forms & Features

Large macromolecules are constructed from smaller subunits.

	Forms	Features
Carbohydrates	Sugars and starch	Energy source; Structural units
Proteins	Amino acids and Proteins	Enzymes; Structural units; Energy source
Nucleic Acids	Nucleotides, RNA, DNA	Genetic instructions; Cellular energy units
Lipids	Fats, oils, and steroids	Hydrophobic; Energy source

Dehydration synthesis

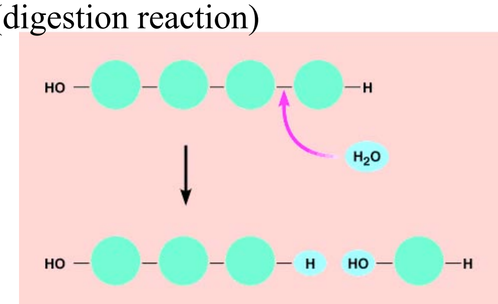
(condensation reaction)



Dehydration ("removing water") synthesis:
Forming polymers produces water as a byproduct.

Hydrolysis

(digestion reaction)



Hydrolysis ("water breaking") is opposite of dehydration synthesis.
Breakdown of a polymer requires water

Organic Macromolecules

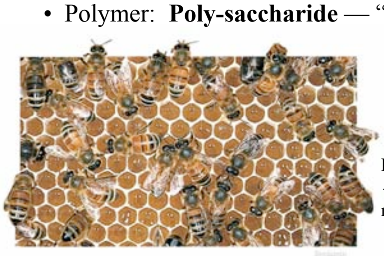
Monomers & Polymers

Large macromolecules are constructed from smaller subunits.

	Subunit	Macromolecule
Carbohydrates	Monosaccharide	Polysaccharides
Proteins	Amino acid	Polypeptide
Nucleic Acids	Nucleotides	RNA, DNA
Lipids	Fatty acids + glycerol or other carbon backbone	Triglyceride, wax, phospholipid

1. Carbohydrates

- Used for: Energy, structure
- Monomer: **Mono-saccharide** — "one sugar"
- Polymer: **Poly-saccharide** — "many sugars"



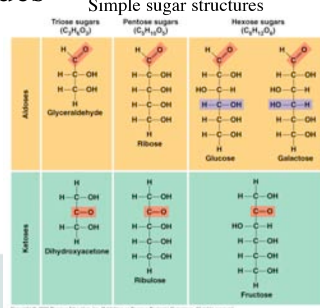
Bees with honey — a mix of 2 monosaccharides

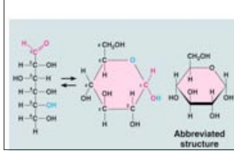
Monosaccharides

"single sugar"

- **Molecular formula: $n(CH_2O)$ n = 3–7**
  - **C_3 sugar: triose**
  - **C_5 sugar: pentose**
  - **C_6 sugar: hexose**

Simple sugar structures

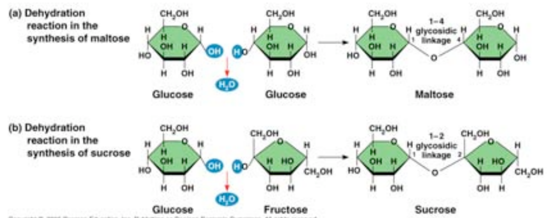




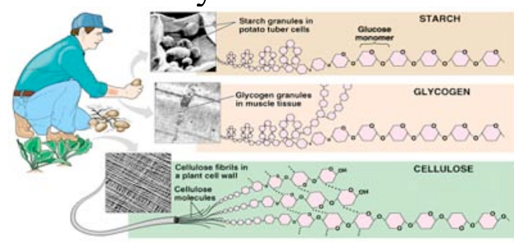
- Glucose [a type of hexose] is main circulating energy source for animal cells
- Occurs in alternate linear or circular forms

Disaccharides
“double sugar”

- Cells link 2 single sugars to make 1 disaccharide



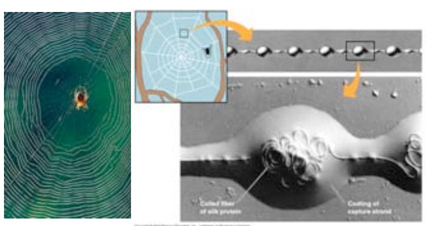
Polysaccharides



- Glycogen is the main polysaccharide in animals, but plants make many varieties (“dietary fiber”).
- Glycogen, starch, and cellulose are all poly-glucose.
- But very different bioactivity (and digestibility) varies because of different chain branching.

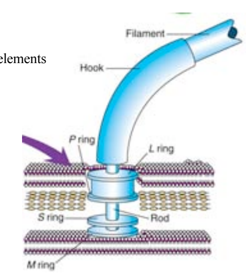
2. Proteins, Essential to Life

- *proteios*: “primary”
- Important for the operation and regulation of all life processes!
- *“Proteins run everything!”*



2. Proteins, Essential to Life

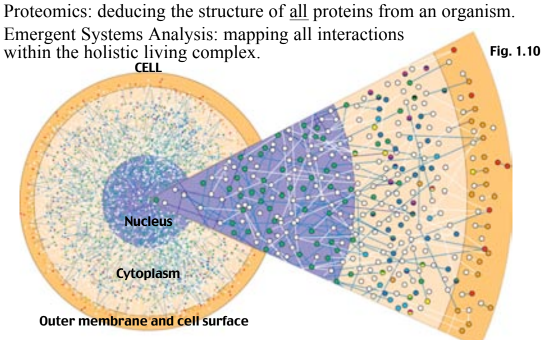
- Structural
  - E.g., collagen & keratin
- Transport
  - E.g., hemoglobin
- Movement
  - E.g., muscle filaments & cytoskeletal elements
- Communication messengers
  - E.g., insulin & growth hormone
- Communication receivers
  - E.g., hormone and neural receptors
- Selective cellular permeability
  - E.g., membrane gates & pumps
- Defense
  - E.g., antibodies
- Enzymes
  - E.g., RNA-polymerase
  - Regulate all biochemical reactions



Bacterial flagellum

Proteomics and Emergent Systems

- Proteomics: deducing the structure of <u>all</u> proteins from an organism.
- Emergent Systems Analysis: mapping all interactions within the holistic living complex.



A systems map of known interactions among 3500 proteins in a fly cell

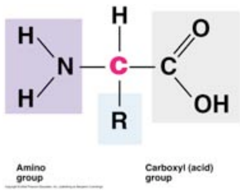
2. Proteins, Essential to Life

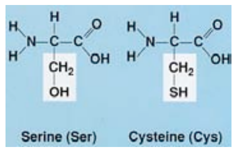
- Monomer: **Amino Acid**
  - 20 different amino acids used to make proteins
- Polymer: **Polypeptide**
  - The precise sequence of amino acids in the polypeptide determines the function of the protein

Hair made of keratin,
a structural protein

Proteins are made from Amino Acids

Amino acid structure



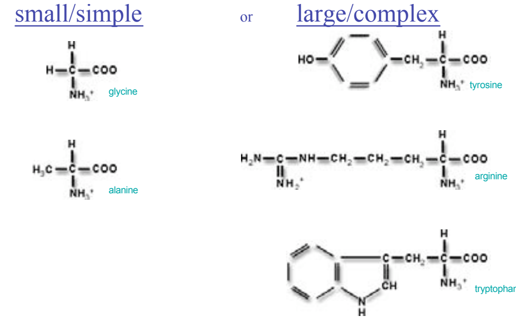


Different R-groups define different amino acids

- All amino acids have an amino group, a carboxyl group, and an R group
- R groups define a specific amino acid

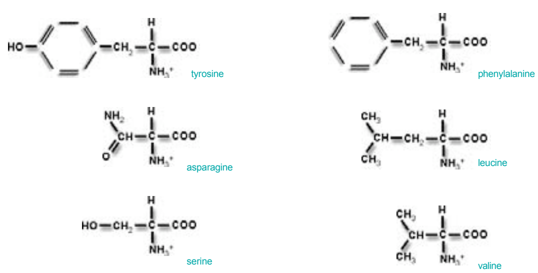
amino acid R-groups may be

small/simple or large/complex



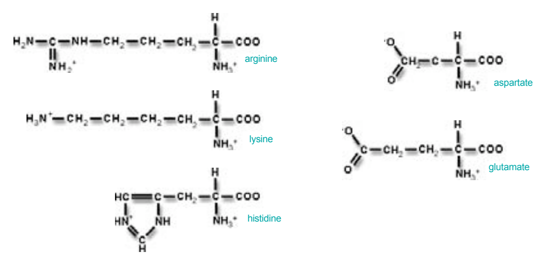
amino acid R-groups may be

polar or nonpolar



amino acid R-groups may be

cationic or anionic



Charge is dependent upon pH

20 amino acids used in protein synthesis

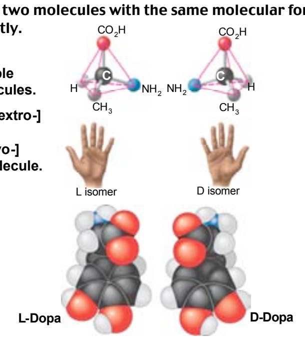
Group I: nonpolar	Group II: polar	Group III: charged
Alanine (A)	Asparagine (N)	Arginine (R)
Isoleucine (I)	Cysteine (C)	Aspartic Acid (D)
Leucine (U)	Glutamine (Q)	Glutamic Acid (E)
Methionine (M)	Glycine (G)	Histidine (H)
Phenylalanine (F)	Serine (S)	Lysine (K)
Proline (P)	Threonine (T)	
Tryptophan (W)	Tyrosine (Y)	
Valine (V)		

Stereo Isomers (Enantiomers)

Isomer ("same unit"): two molecules with the same molecular formula, but arranged differently.

Enantiomers: Non-superimposable mirror image molecules.

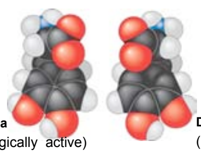
"Right-handed" [Dextro-] & "Left-handed" [Levo-] versions of the molecule.



Stereo Isomers (Enantiomers)

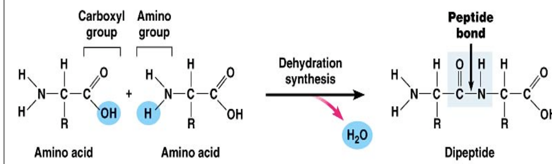
One of the great mysteries of the origin of living cells –

- **All non-biological synthesis reactions of organic molecules produce <u>both</u> D- and L- isomers in equal yield.**
- **And all non-biological reactions using organic molecules as reactants react with <u>both</u> D- and L- isomers equally.**
- **Yet, living cells are constructed <u>only</u> of D-sugars and their derivatives, and only L-amino acids and their derivatives!**



L-Dopa (biologically active) **D-Dopa** (biologically <u>in</u>active)

Peptide Bonds Link Amino Acids

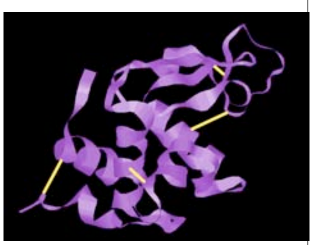


Peptide bond formation

- Amino acids linked by dehydration synthesis
   "peptide bond"
- Polymer of amino acids = polypeptide
- Different polypeptides have different amino acid sequences

Protein Shape Determines Function

- Specific 3-D shape
- **Shape is critical to function**



Ribbon model of lysozyme protein

- **Denaturation** = loss of shape and function

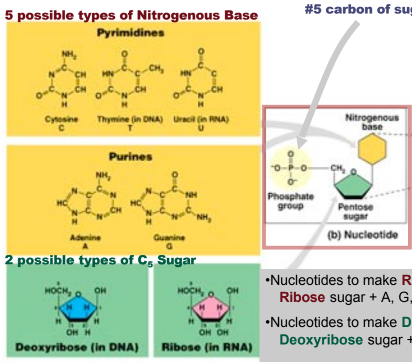
3. Nucleic Acids — Information & Energy Carrying Molecules

- Used for:
  - Information (DNA, RNA)
  - Cellular Energy (ATP)
- Monomer:
  - **Nucleotide**
- Polymer:
  - **Nucleic acid**

Human chromosomes

Nucleotides

- **5 possible types of Nitrogenous Base**
- **1, 2, or 3 phosphates off #5 carbon of sugar**

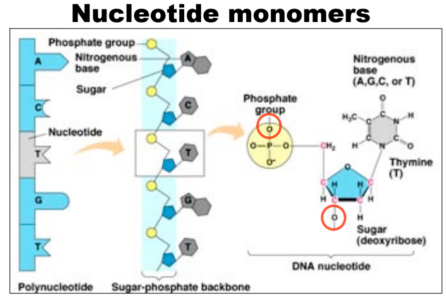


- **2 possible types of C_5 Sugar**

•Nucleotides to make **RNA** = **Ribose** sugar + A, G, C, or **U** base

•Nucleotides to make **DNA** = **Deoxyribose** sugar + A, G, C, or **T** base

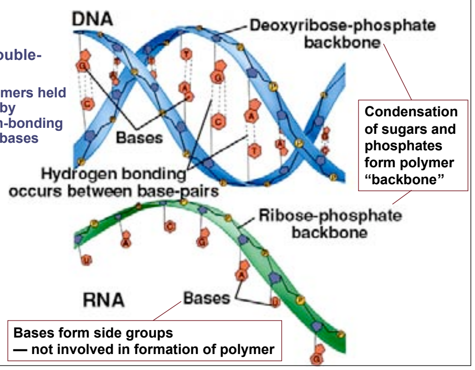
<u>Nucleic Acids</u> are linear polymers of Nucleotide monomers



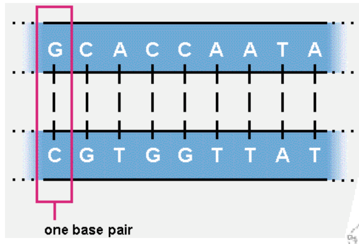
Condensation reaction between
•phosphate on #5 carbon of the sugar in one nucleotide, and
•the hydroxyl on #3 carbon of the sugar in the other nucleotide
Polymer forms sugar-phosphate-sugar-phosphate-sugar-phosphate-… linear chain with nitrogenous bases to the side

Nucleic Acids — linear polymers

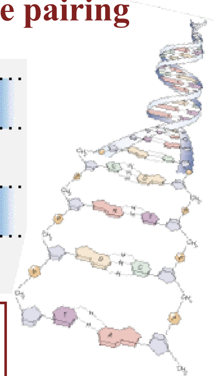
- DNA is "double-stranded"
  - Two polymers held together by hydrogen-bonding between bases



complementary base pairing



Complementary base pairing in DNA
- **C pairs only with G**
- **A pairs only with T**



complementary base pairing

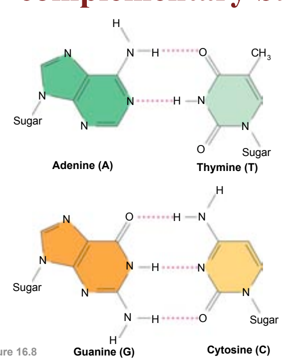
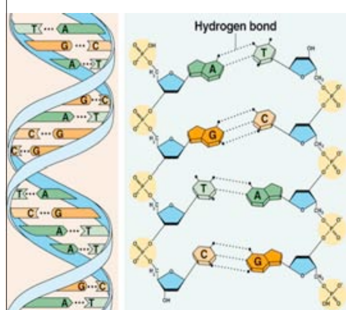


Figure 16.8

Each pair
= 1 purine + 1 pyrimidine

- A=T (2 H-bonds)
- G≡C (3 H-bonds)

dsDNA Structure



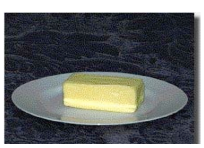
DNA's complementary base sequence

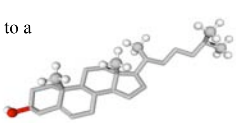
 the sequence of bases in the two strands are **complimentary** to each other (*not* identical).

4. Lipids
— Include Fats and Cholesterol

- Used for:
  - Energy storage, insulation, steroids, vitamins
- Subunit:
  - fatty acids
- Macromolecule:

(not a polymer — subunits attached to a different carbon backbone)
  - triglycerides & phospholipids
  - sphyngolipids
  - waxes



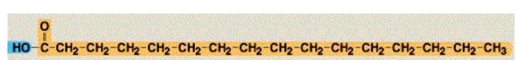


Cholesterol, a modified fatty acid

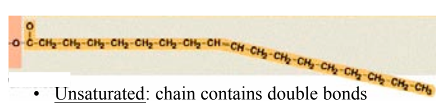
Fatty Acids

- Long C_{8-16} hydrocarbon "tail" = non-polar = hydrophobic = "fatty"
- Carboxyl "head" = acid

 "**Fatty Acid**"



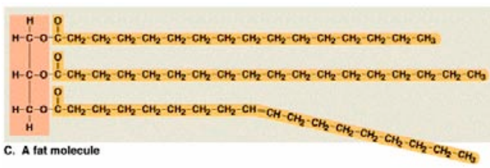
- Saturated: all C-C single bonds
  - Two hydrogens on each carbon



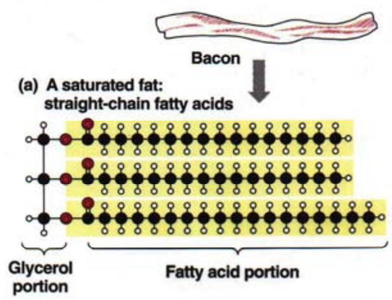
- Unsaturated: chain contains double bonds
  - Causes rigid kinks in chain

Triglycerides

- Tri = three; glyceride = on glycerol
- Formed by dehydration synthesis of fatty acid side-chains linked onto glycerol
  - One fatty acid on the glycerol = monoglyceride = acyl-glycerol
  - Two fatty acids on the glycerol = diglyceride = diacyl-glycerol [DAG]
  - Three fatty acids on the glycerol = triglyceride = triacyl-glycerol [TAG]
- Storage form of lipids

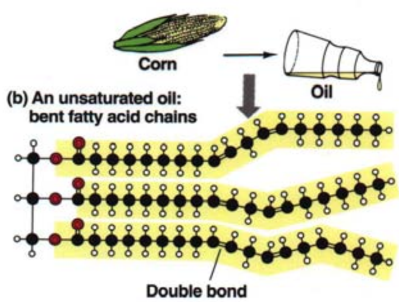


Saturated fat forms solids at room temp (animal fat)



Animal fat is a mixture of triglycerides with >50% of fatty acids saturated.

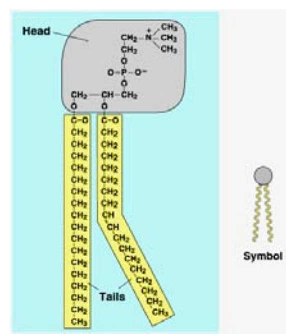
Unsaturated fats are liquid at room temp (vegetable oil)



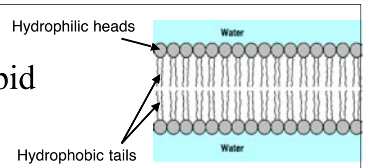
Plant oil is a mixture of triglycerides with <15% of fatty acids saturated.

Phospholipids

- Used to make cell membranes
  - Plasma membrane
  - Cell membranes
- Phosphate:
  - **Hydrophilic "head"**
- 2 Fatty acid chains:
  - **Hydrophobic "tail"**



Phospholipid Bilayer



- Hydrophilic "heads" associate together
  - Form outer layer of cell membrane
- Hydrophobic "tails"associate together
  - Form inner layer of cell membrane
  - Keep water soluble molecules from crossing membrane
- Form **double layer** of cell membranes

Isolated activity compartments