Part II of course: Origin of Life

The basic idea we will be discussing assumes that life arose as a sequence of increasingly complex chemical reactions, driven by the variety of energy sources present in the early Earth environment. In this model the basic atoms used by life here on Earth, provided by nuclear reactions in stars, became more and more complex molecules ("monomers"--like sugars, amino acids, nucleic acids), which finally made the (difficult) transition to functioning biological molecules ("biopolymers" like lipids, proteins, RNA, DNA or their equivalents). This is sometimes called the "chemical evolution theory," but it is more like a working hypothesis, and there are several different theories, related to a lot of empirical and laboratory evidence, for the details of how this came about.

atoms [C, N, O from stars; H from big bang] —planetary temperatures→ **molecules** [methane, ammonia (??); water vapor, carbon dioxide, hydrogen cyanide HCN, …] —energy→

→ **more complicated molecules** (e.g. amino acids, lipids, nucleic acids) —??→ **proteins** / **membranes** / **a self-replicating molecule (RNA?)** → **coupled DNA,RNA, proteins**

→ (prokaryotic) **cells** (~0.5 billion yr) —evolutionary process→ complex (eukaryotic) **multicellular life** (~3 billion yr)

Here are two visual representations of the general process we have in mind, although details of the order of events (e.g. cells, or metabolism, before genomes? a pre-RNA-self-replicator?

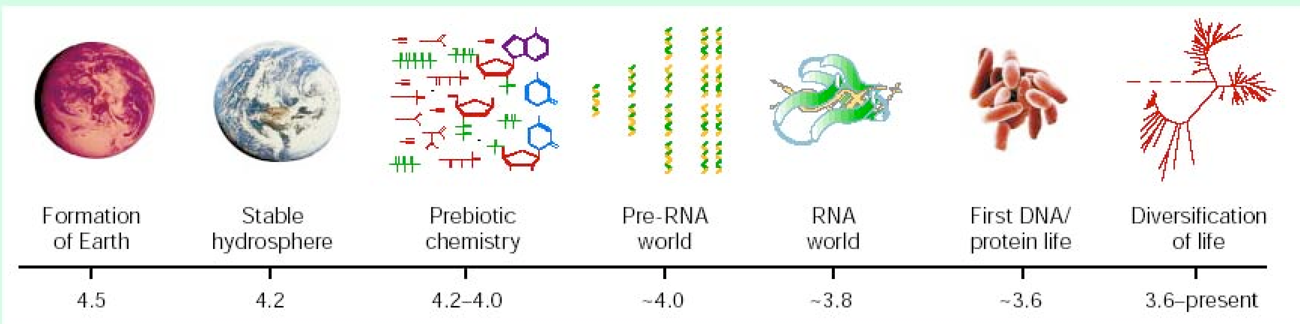
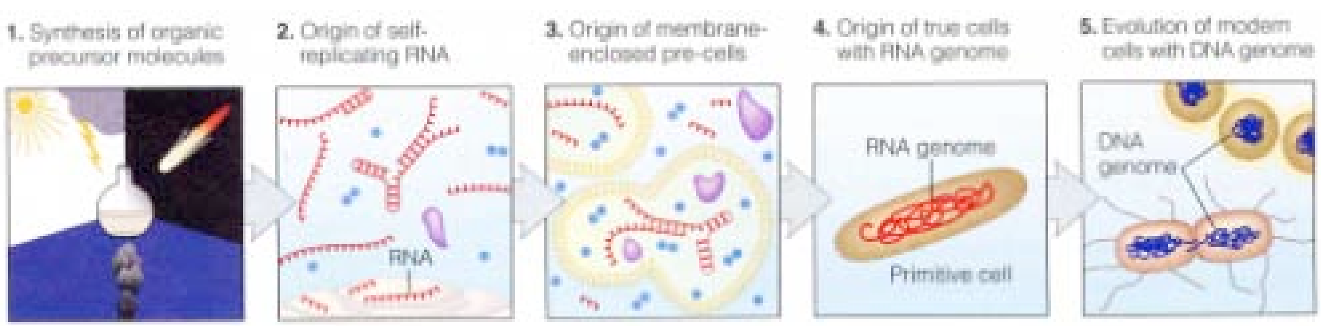


Figure 1 Timeline of events pertaining to the early history of life on Earth, with approximate dates in billions of years before the present.



Here is a more detailed (and colorful!) picture of the kind of developments that we must be able to account for, from monomers (bottom) to complex cells (top):

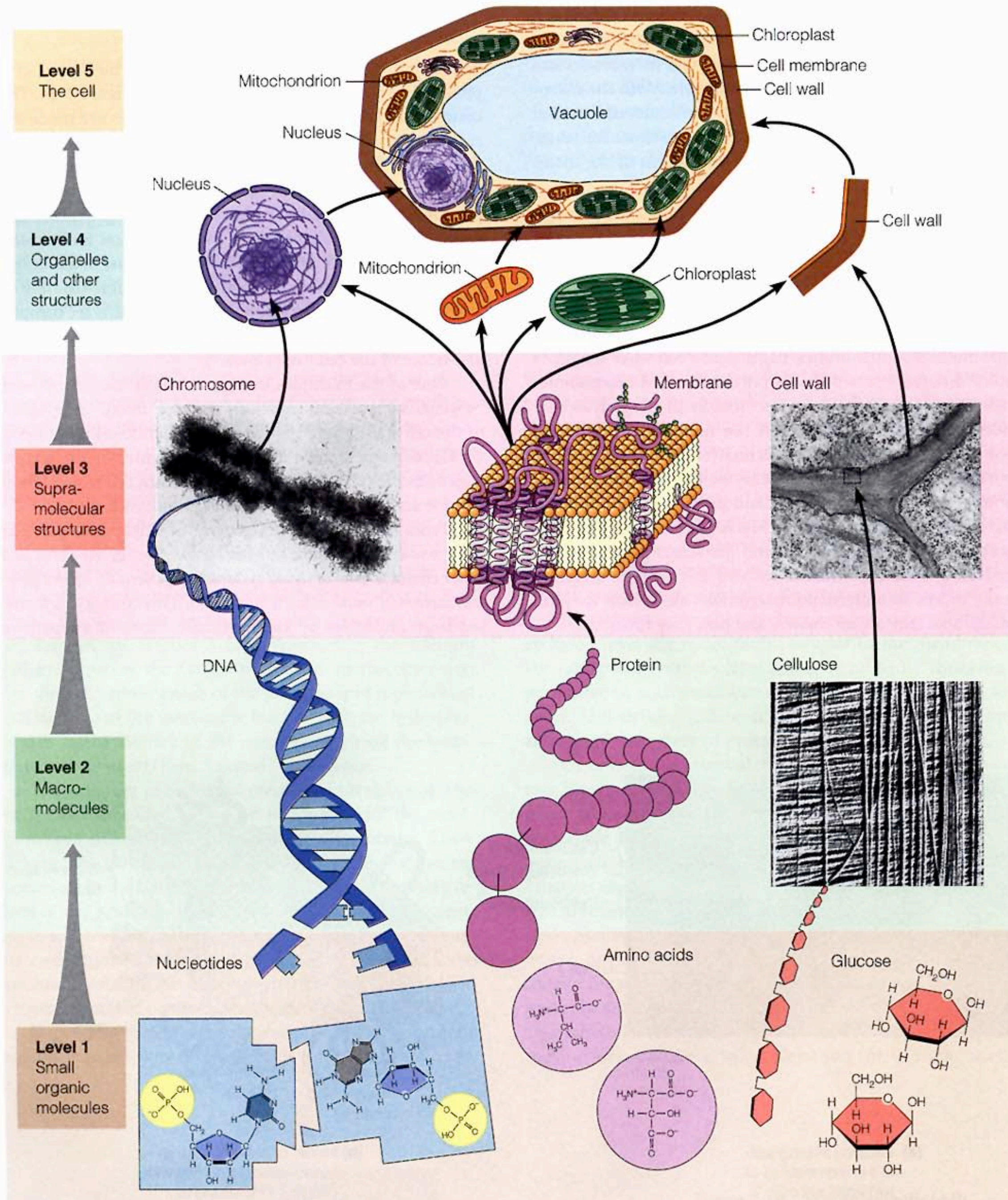


Figure 2-14 The Hierarchical Nature of Cellular Structures and Their Assembly. Small organic molecules (level 1) are synthesized from simple inorganic substances and are polymerized to form macromolecules (level 2). The macromolecules then assemble into the supramolecular structures (level 3) that make up organelles and other subcellular structures (level 4) and, ultimately, the cell (level 5).

What is "life"? (**Not** a trivial question!)

Historically and cross-culturally, several ways of viewing this:

reductionism, mechanism ⟷ emergentism, holism ⟷ vitalism, animism, panpsychism, pantheism

Nearly all the ideas you will read about are to the far-left in this sequence, since that is the realm of science (although there is a little leaning toward the center).

Some suggested attributes of life (or a living process): (no special order; compare with list suggested in textbook)

First, notice that life is a pattern in space and time, *not* a specific material object, e.g. most of our cells are replaced many times. So maybe more like a process or a function or an interaction.

- metabolism ("eating")
- reproduction (w/mutation?)
- sensitivity to external stimuli
- death
- excretion
- processing of matter <u>and</u> information
- increase in order--life locally halts or reverses entropy increase
- morphogenesis-growth, differentiation and evolution of form
- possession of a "genetic" program
- maintenance of a structural boundary
- storage of energy for later use
- utilization of external energy and materials

Notice that no single attribute defines life, and every attribute has a counterexample. **Reproduction *with* genetic-like evolution are today usually considered the primary attributes—as in your text.**

Other important considerations:

1. Information storage of a <u>**self-representation**</u>, e.g. earth organisms store a description of themselves in DNA molecules, interpreted by protein/RNA "machinery." [This is mostly for repair and reproduction. . . But we also have other representations---our sense of "identity," "self-consciousness."]

2. <u>**Functional**</u> interactions with the environment---responds to or anticipates changes in environment.

Problematical example: "Artificial life" cellular automata (discussed later)

The Chemical Basis of Life

Compare abundances of elements in life, Earth, and rest of Universe.

• **Life**---4 types of atoms account for >97% of the atoms in living things:

hydrogen (H),	oxygen (O),	carbon (C),	nitrogen (N)
~60%	~25%	~10%	~2%

+<u>phosphorus</u>, sulfur, and calcium (about 0.1% each)
+trace elements (e.g. iron, zinc, magnesium, manganese, . . .) <0.01%

• **Earth**---mostly oxygen (47%) + silicon (28%)

+ Fe, Mg, Al, S, Ni, Na, Ca, P,... C,... N

But this includes the land masses; if we only include oceans and atmosphere, H, O, C, N may have been most abundant.

Abundances of trace elements in bacteria, plants, land animals, *may* correlate with abundances in sea water. [Not so easy to demonstrate quantitatively!]

This suggests that life began in oceans (not so certain) *and* that life arose on Earth, **not** elsewhere ("panspermia"). *Or* that water and life were delivered together! (Comets, asteroids, …) We'll return to evidence related to this later.

• **Sun + Stars**---remarkable uniformity [abundances derived from analyses of spectral lines]. [These are abundances by number, not mass.]

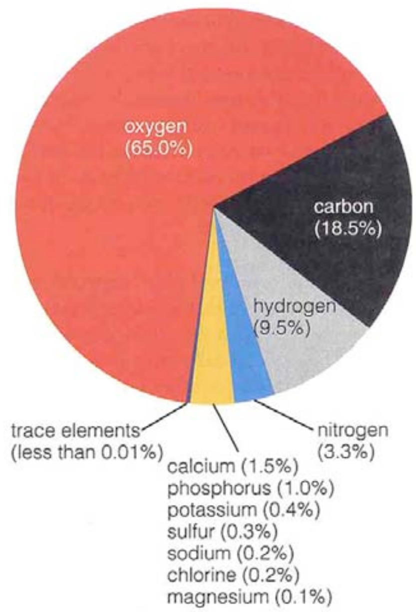
H 93% [*He, Ne are "noble gases," unreactive]
^{4}He <u>7%</u>

everything	O	0.06%	*Ne	0.02%		
else ~0.1%	N	0.01%	C	0.03	....	.

So H, C, N, O most abundant in stars and universe as well as in life.

→ Suggests that our type of life, HCNO (+important trace elements), is the most likely type in the universe, based on availability.

A pie chart showing the composition of the human body is shown on the next page.



This pie chart shows the chemical composition of the human body by weight; this composition is fairly typical of all living matter on Earth.

More support for this conclusion:

• discovery of amino acids and other biologically-related molecules in meteorites (350, compared to 46 on earth)*; sugar discovered in 2001. See Table below. You will soon become familiar with the types of molecules listed!

• discovery of complex prebiological molecules in interstellar space (discussed in Part I of the course).

*1994:Biologist Carlisle claims at least 2 of them are dandruff

The biological role and types of organic molecules (both monomers and polymers) found in life and in meteorites.

	Role	Life	Murchison meteorite
water	solvent	yes	yes
lipids (hydrocarbons and acids)	membranes, energy storage	yes	yes
sugars (monosaccharides)	support, energy storage	yes	yes
polysaccharides (polymerized sugars)		yes	no
amino acids	many (support, enzymes, etc.)	yes	yes
proteins (polymerized amino acids)		yes	no
phosphate	genetic information	yes	yes
nitrogenous bases		yes	yes
nucleic acids (polymerized sugars, phosphates and nitrogenous bases)		yes	no

Molecules of Life

A. Basic chemistry

atoms → nucleus (pos. charge) → protons (+) and neutrons (no charge)
atoms → electrons (negative charge)

Atomic number = number of protons (e.g. 6 for carbon C): unique characteristic of each element
Atomic mass (or weight) = number of protons plus neutrons (e.g. 12 for ^{12}C).

	^{1}H	^{4}He	^{12}C	^{14}N	^{16}O
# protons:	1	2	6	7	8

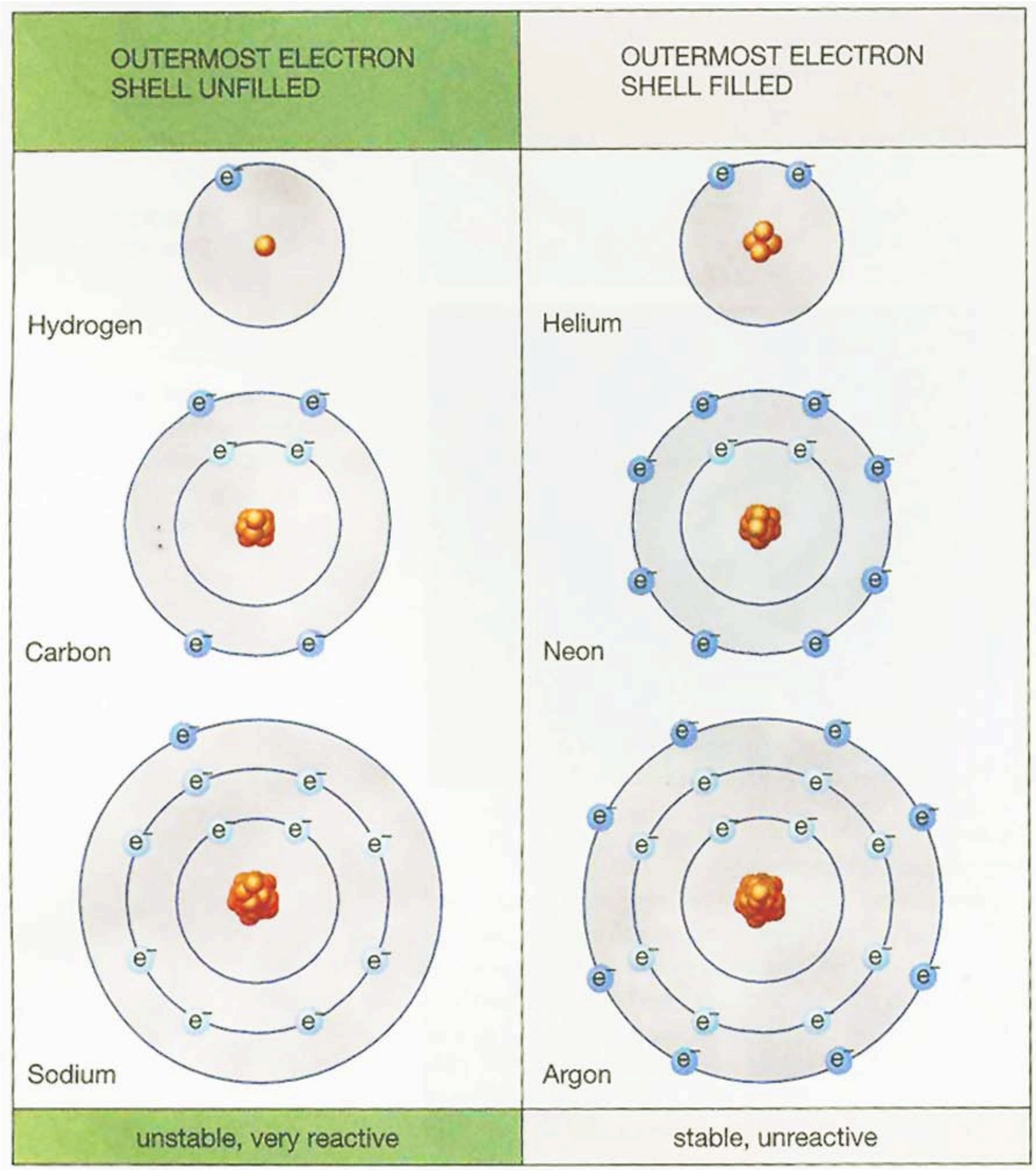
If atom is in its (normal) neutral state, then the #electrons = #protons. If the #electrons is greater or less than #protons, then we refer to it as a (negative or positive) ion.

Isotopes: same element but different number of neutrons
e.g. ^{2}H (deuterium), ^{3}He, ^{13}C (~1% of C), ^{14}C (about 10^{-12} of C in earth's atmosphere).
Too many neutrons: isotope is radioactively unstable, decays with certain half-life (e.g. ^{14}C, 5780 yr). We'll return to this when discussing ages of rocks, fossils)

• electrons occur in electron shells or orbitals at different distances from the nucleus (corresponding to different energies). **Notice that this *quantized* nature of the particle energies is, at the most fundamental level, the ultimate prerequisite for life as we know it, because that's what gives rise to all chemical possibilities**. No one knows *why* our universe is quantized, but it apparently is.
• electrons in shells closer to nucleus have lower energies, those farthest away have most energy
• electrons move to lowest possible energy level. (e.g. In photosynthesis, sunlight kicks e's in chlorophyll out of low-energy shells to higher-energy shells; as they return to low-energy shells, some of the "extra" energy is used to power synthesis of sugar from CO_2 and H_2O)
• innermost shell can hold 2 electrons; 2nd, 3rd,...shells can hold 8 electrons.
If outer shells are filled: most stable atoms (e.g. He, Ne, Ar,...) ⇒ no chemical reactions
If outer shells unfilled (most atoms): atom can take part in chemical reactions in which they gain, lose, or share electrons with other atoms, forming bonds ⇒ molecules

Examples. H: only 1 electron, so room for 1 more.
C: 6 electrons, 2 inner shell, 4 in 2nd shell ⇒ room for 4 more
O: 8 electrons, 2 inner shell, 6 in 2nd shell ⇒ room for 2 more

The number of unfillled outer shell electrons is what (mostly) determines what kind of bonds and therefore molecules you can form with a given atom.


OUTERMOST ELECTRON SHELL UNFILLED
OUTERMOST ELECTRON SHELL FILLED
Hydrogen
Helium
Carbon
Neon
Sodium
Argon
unstable, very reactive
stable, unreactive

Making Molecules
Three types of bonds between atoms

1. Ionic bonds (ion = atom that has lost or gained one or more of its outermost electrons)

This type of bond is formed by the electrical attraction between + and - ions in order to have more stable (i.e. filled) outermost shells. The result is called an "ionic compound" (not a molecule strictly).

The classic example is table salt, sodium chloride (NaCl).

Na: 11p, 11e (2, 8, 1) ⇒ outer shell has only 1 electron

Cl: 17p, 17e (2, 8, 7) ⇒ outer shell has 7 electrons, only needs 1 more for stability.

So Cl reacts with Na, "stealing" Na's lone outer electron > both Cl and Na now have stable (8e) outer shells.

But now Na has + charge, Cl has - charge, so they attract ⇒ ionic bond.

These NaCl tend to join together (because they are completely polarized in charge) to form a crystal structure, which is salt.

2. Covalent bonds -- two atoms *share* a pair of electrons (one from each atom), so that each atom has a stable complete outer shell.

Example: molecular hydrogen H_2 -- two H atoms share their lone electrons, so each atom behaves as though it had a filled shell of 2 electrons.

Double covalent bonds: each atom contributes *two* electrons.

Example: C atom requires 4e to fill its outer shell, O atom requires 2e to fill its outer shell. So can form O=C=O (CO_2, carbon dioxide). The C atoms shares 2e with each O atom, so all three atoms fill their outer shells.

Polar covalent bonds: different atoms have different strengths of attraction for electrons ("electronegativity"). Generally, more electronegative atoms are smaller and have nearly filled outer shells.

So when two different atoms bond covalently, the more electronegative atom attracts e's more strongly, so e's spend more time there, creating partial negative charge (δ^+), but atom at other end acquires partial positive charge (δ^+).

Example: O and N much more electronegative than H, so when either bonds with H, get polar bonds (e.g. H_2O). CO_2 and H_2O have strong covalent bonds, but some are weak, e.g. O_2, or gasoline, which are less stable and therefore very reactive. **We'll see that the relatively strong polar covalent bonds in H_2O are what give it some of its unique properties.**

Occasionally covalent bonding leaves one atom with an unpaired electron, a potentially harmful situation ⇒ free radicals. For example, you should think about the electron pairing that can occur between N (5 outer electrons, needs 3) and O (6 outer electrons, needs 2) to make N=O (nitric oxide), leading to a single unpaired electron (around the N). Another example is OH. Because of the unpaired electron, these free radicals seek partners ⇒ highly reactive ⇒ a major source of mutations induced this way (⇒ cancer, DNA damage, aging,..., but also a driver for diversity and evolution at the genetic level).

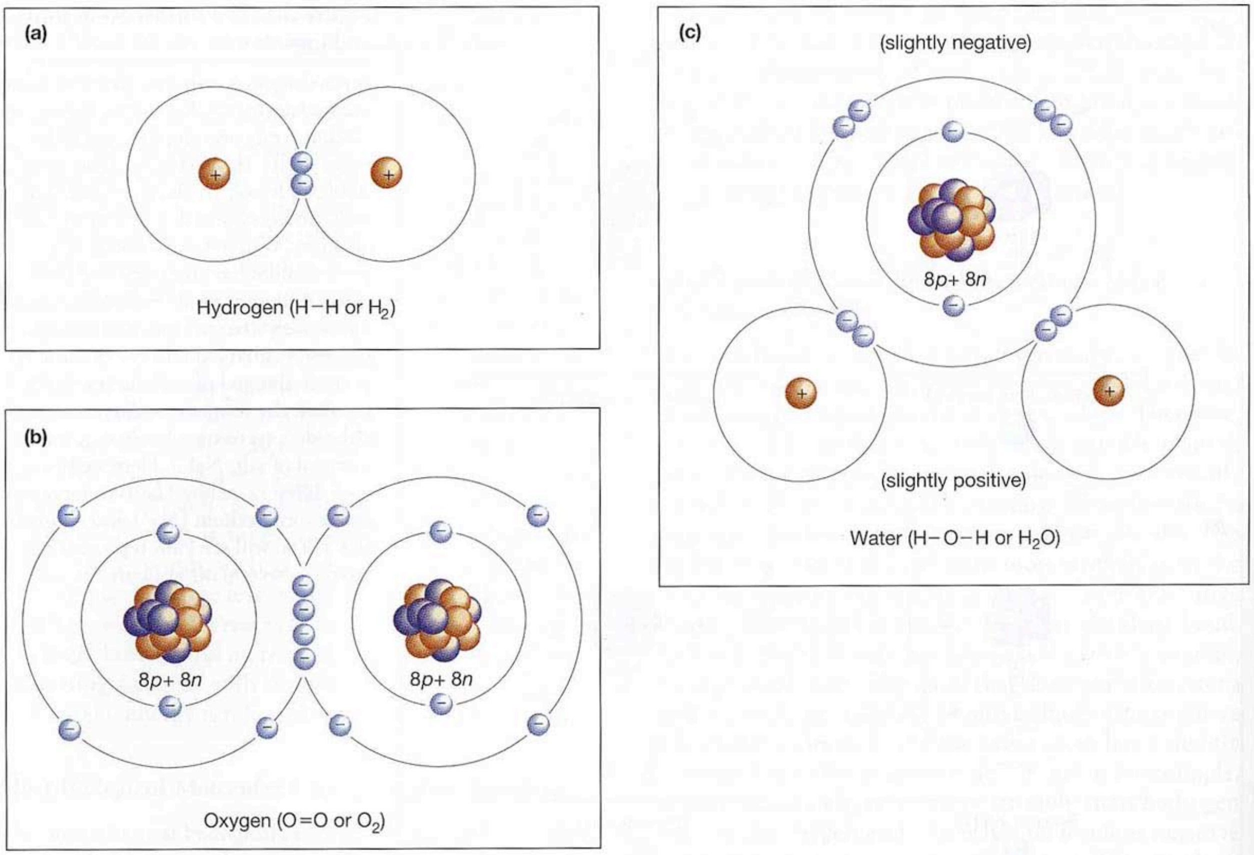


Figure 2-6 Covalent bonds

The most common elements in living organisms are the smallest (and most abundant) ones capable of forming 1, 2, 3, 4, and 5 covalent bonds.

Here is a table of the main biologically-important atoms and their bonding tendencies.

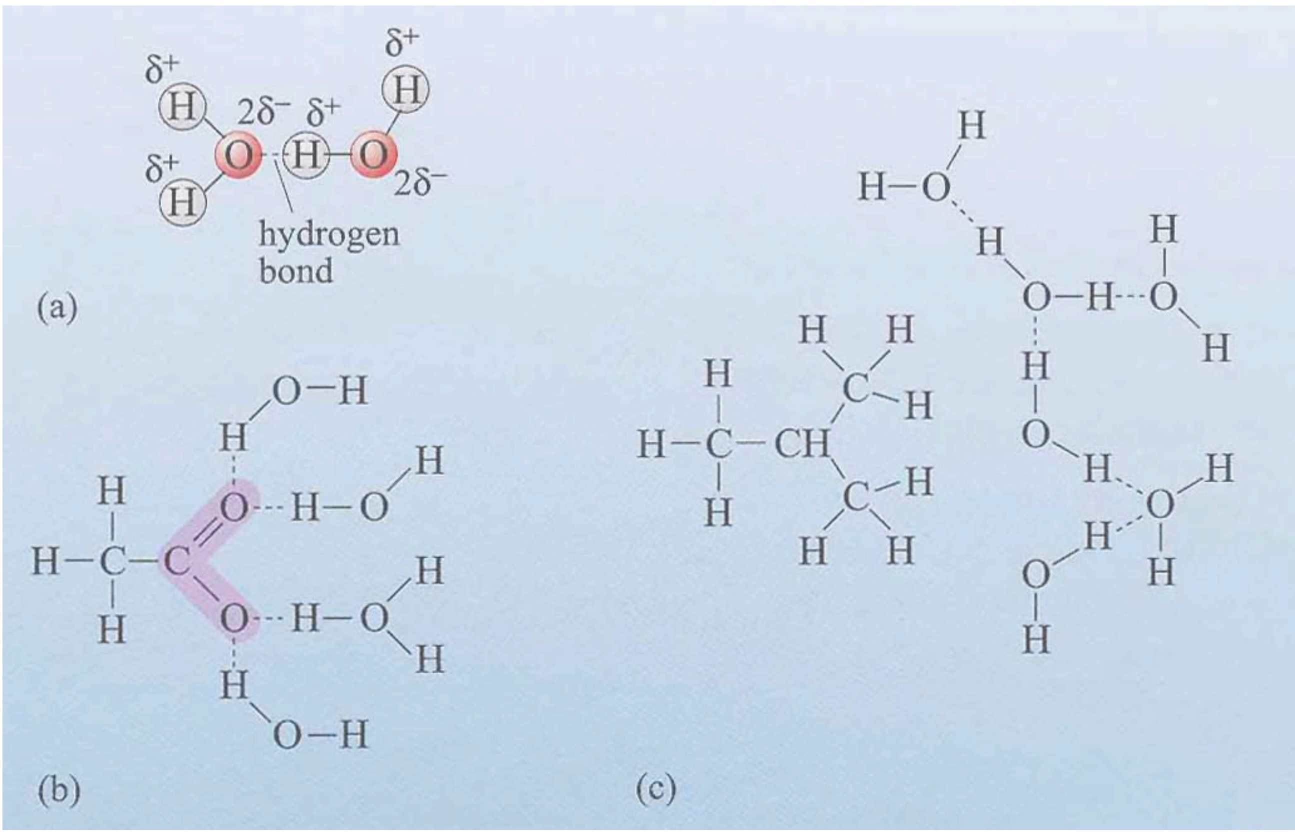
Atom	Capacity of outer electron shell	Electrons in outer shell	# covalent bonds usually formed	common bonding pattern
H	2	1	1	–H
C	8	4	4	–C– –C= =C= –C≡
N	8	5	3	–N– –N= N≡
O	8	6	2	–O– O=
K(phosphorus)	8	5	5	–P =
S (sulfur)	8	6	2 (up to 6)	–S–

3. Hydrogen bonding – This last variant of bonding plays a crucial role not only in linking molecules of a single molecule together, but in creating bonds *between* molecules. It is a fundamental feature of the structure of proteins, RNA, and DNA.

An important example will illustrate the process.

Recall that water is an example of a polar covalently bonded molecule, with the O-end having a slight negative charge and the H-end having a slight positive charge. So when you place several water molecules together, a positive H atom of one molecule is weakly attracted to the negative, *unshared* electrons of its oxygen neighbor. This is a **hydrogen bond**, linking an already covalently bonded H atom with some electronegative atom (in this case O, but nearly always either O or N).

The figure below shows the importance of hydrogen bonding for water. (a) Water molecules carry a partial positive charge on H atoms and partial negative charge on O atoms that can interact to form a hydrogen bond. (b) Water molecules interact with polar organic molecules. (c) Apolar organic molecules do not interact with water molecules.



Why Carbon?

Carbon's importance stems from its bonding capacity. With 4 outer shell electrons, it needs to link with 4 more to achieve stability ("tetravalent"), but can also form molecules with a smaller number of bonds.

Major advantages:

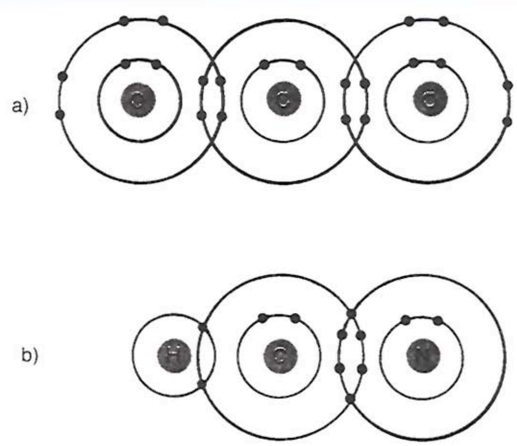
1. C forms stable molecules – strong covalent bonds

C-C 83 kcal/mol	C=C 146	(1 mole - 6×10^{23} bonds
C-N 70	C≡C 212	1 cal = 4.184 Joule)
C-O 84		
C-H 99		

So specific enzymes capable of releasing a large amount of energy are needed to break these bonds.

Also, visible light is unable to break covalent bonds, *but* UV *can* ⇒ hazard because of cell damage; but also the source of mutations (and therefore evolution).

Here is a picture of how carbon makes covalent bonds in producing CO_2 and HCN.



A carbon atom has four electrons in orbit in its outer electron shell. These electrons can be shared with other atoms to bind carbon into molecules. Some of the different ways in which these bonds can form include (a) sharing two electrons with each of two oxygen atoms to make one molecule of carbon dioxide (CO_2), and (b) sharing three electrons with a nitrogen atom and one electron with a hydrogen atom to make one molecule of hydrogen cyanide (HCN).

2. C-containing molecules are diverse. Can bond with other C atoms to make long chains (e.g. in lipids) and rings (e.g. benzene, or, with other atoms, the bases that are used to make nucleic acids). (See figure below.) Further variety is possible by side-branching (often using certain characteristic "functional groups") or double or triple (e.g. CH≡CH, acetylene) bonds. See pictures of membrane lipids, amino acid structure, and nucleic acids.

When H atoms are used to complete valence requirements of such molecules, the compounds are called hydrocarbons (e.g. octane, an 8-carbon compound C_8H_{18}). These are insoluble in water, but that is why they are so important (tails of phospholipid membrane molecules, something we already mentioned in connection with hydrophobic molecules).

C also combines with O, N, P, S in various functional groups (phosphoryl, amino, ...) whose details are beyond the scope of this introductory material.

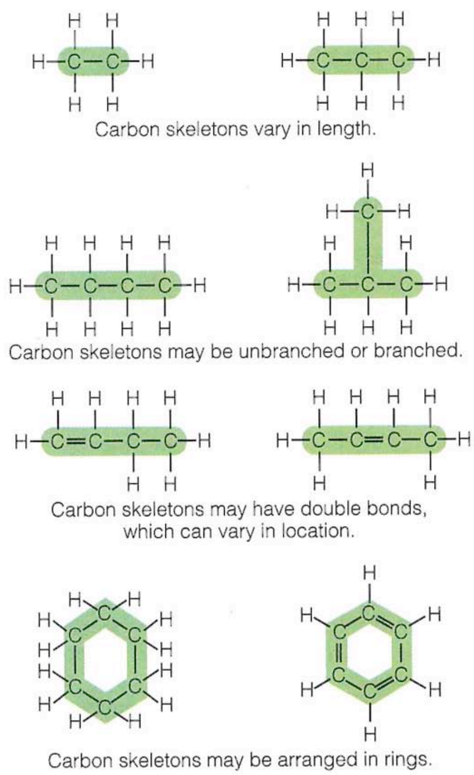
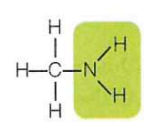


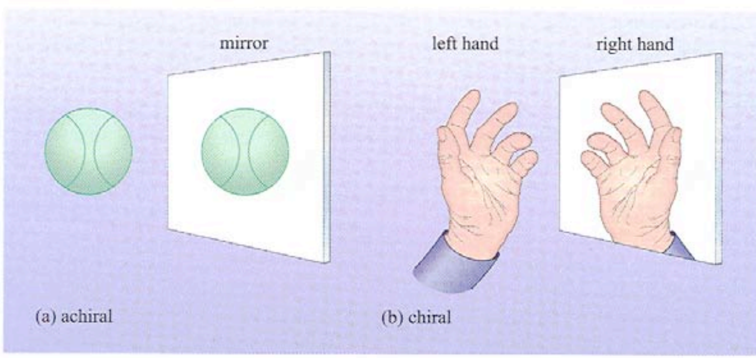
FIGURE 3.8 These diagrams represent several relatively simple hydrocarbons —organic molecules consisting of a carbon skeleton attached to hydrogen atoms. The carbon skeletons are highlighted in green. Each single line represents a single chemical bond; a double line represents a double bond. Note that every carbon atom has a total of four bonds (a double bond counts as two single bonds).

FIGURE 3.9 In a more complex organic molecule, at least one bond links a carbon atom to something besides hydrogen or another carbon atom. Here, one of the carbon atom's four bonds links it to an *amino group* (which consists of a nitrogen atom and two hydrogen atoms), highlighted in green.

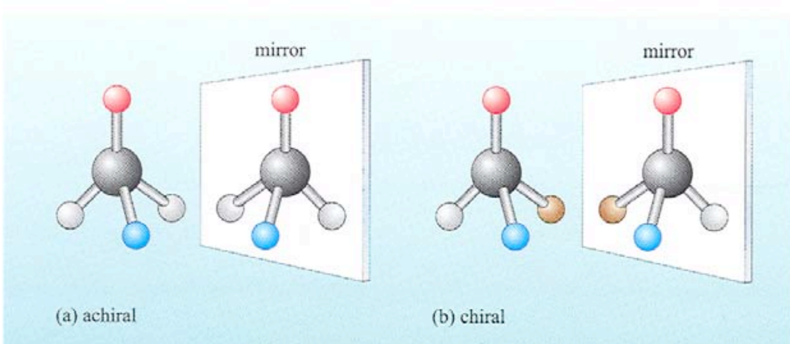


3. Carbon forms sterioisomers – carbon can make tetrahedral structures with geometric symmetry, but can have two mirror-image forms that are called sterioisomers. E.g. amino acids (alanine example shown in class). Only the L-form (not D) used in biological molecules. This property is called "***chirality***." No one knows why all living things exhibit this chirality, what caused it (there are many suggestions), or how essential it is, although most people appear to think it is a big clue to the origin of life.

Whatever its origin, if chirality is essential, then it gives us a handy way to look for biosignatures. For example, in meteorites the amino acids found are "racemic" (equal mixtures of L and D), not chiral, suggesting that they were not biological. If someone found a "Mars meteorite" (discussed later in course) that had a chiral bias, that would be strong evidence that there was life on Mars! If we examine potential candidates other than C, we find that each of them *are* essential for ife as we know it, but not in the same fundamental, structural way that C is. (Discussion in class.)



(a) The mirror image of a ball is superimposable on the original object and is therefore achiral. (b) The mirror image of a hand is not superimposable on the original and is therefore chiral.



(a) An achiral molecule. Its mirror image can be superimposed on the original. (b) A chiral molecule. The mirror image cannot be superimposed on the original.

Why not an element other than C? If we examine the list of potential candidates, we find that each of them are essential for life as we know it, but not in the same fundamental, structural way that C is.

Hydrogen H: Crucial for lots of bio-molecules, but only forms one bond at a time, so always a dead-end; can't link together to form chains or rings.

Oxygen O. Important, since no sugars or amino acids without 0, and of course most of our terrestrial energy sources depend on it for energy. However it does not form complex molecules like C does. Normally 0 forms 2 bonds, either with one atom (e.g. 0=0, O_2) or two (water H-O-H, H_2O). Very reactive, can bond with many different atoms, but can only bond with 1 or 2 atoms at a time. Also, chains of >2 O's are unstable. The only two *stable* molecules containing only O and H are water and hydrogen peroxide (H-O-O-H, H_2O_2).

Nitrogen N. No cell membranes without hydrocarbons (which involve N by definition), so this is an important element for life (unless you can think of another way to make effective cell membranes). However as the "backbone" of biomolecules, it doesn't do much better than O, even though it can make 3 bonds. The only stable molecules containing just N and H are ammonia (NH_3) and hydrozine (N_2H_4). Long chains of N are not found.

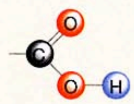
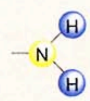
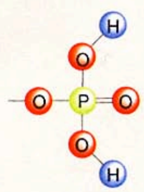
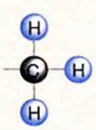
Silicon Si. Only ~1/10 as abundant as C, but *does* form 4 bonds, like C. Silicon's bonds with itself are about half as strong as C-C. But this is only a matter of degree, and life *does* use some weaker bonds, especially to derive energy. Unfortunately for silicon-life enthusiasts, these Si compounds are quite inert; e.g. CO_2 undergoes reactions very easily, but SiO_2 doesn't (that's why it's good for glassware!).

And for some reason (unknown to me, but presumably understood by quantum chemists), Si doesn't form chains and rings in the gas phase. In the solid phase it makes crystal lattices, and in fact most of the earth's crust is made of "silicates" involving the SiO_2 molecule.

We'll see later that there is a theory that claims that life began as rocks! Actually, layered clay minerals. There is very little evidence for this extreme speculation, but many astrobiologists *do* think that silicates were very important for helping to get the pre-biological molecules to chain together into long *biopolymers* (discussed below).

Biological molecules form "**functional groups**," small molecules that attach to other molecules to result in a variety of processes. (You don't have to know these groups—they are just for your information or interest.)

TABLE 3-1 *Important Functional Groups in Biological Molecules*

Group	Structure	Properties	Types of Molecules
Hydrogen (–H)		Polar or nonpolar, depending on what atom hydrogen is bonded to; involved in condensation and hydrolysis	Almost all organic molecules
Hydroxyl (–OH)		Polar; involved in condensation and hydrolysis	Carbohydrates, nucleic acids, alcohols, some acids, and steroids
Carboxyl (–COOH)		Acid; negatively charged when H^+ dissociates; involved in peptide bonds	Amino acids, fatty acids
Amino (–NH_2)		Basic; may bond an additional H^+, becoming positively charged; involved in peptide bonds	Amino acids, nucleic acids
Phosphate (–H_2PO_4)		Acid; up to two negative charges when H^+ dissociates; links nucleotides in nucleic acids; energy-carrier group in ATP	Nucleic acids, phospholipids
Methyl (–CH_3)		Nonpolar; tends to make molecules hydrophobic	Many organic molecules; especially common in lipids