CHAPTER 2 THE ORIGIN AND CHEMISTRY OF LIFE

CHAPTER OUTLINE

2.1. Spontaneous Generation of Life?

A. **History**

1. **Spontaneous generation** was a belief that frogs could arise from earth, mice from rotten matter, etc.
2. In 1861, Louis Pasteur demonstrated sterilized broth in flasks, even exposed to air, could not spontaneously ferment.
3. However, Oparin and Haldane independently proposed a long period of "abiotic molecular evolution" stating life did once arise from nonliving chemistry. **(Figure 2.1)**

2.2. Water and Life (Figure 2.2)

1. Life on earth depends on the properties of water.
   a. Water has a high specific heat capacity; this ability protects organisms from extreme thermal fluctuations.
   b. Water has a high heat of vaporization; this allows terrestrial organisms to cool themselves by removing excess heat.
   c. Water has a unique density behavior; ice is less dense than liquid water. **(Figure 2.3)**
   d. Water has a high surface tension that lends to its great cohesiveness. **(Figure 2.4)**
   e. Water has a low viscosity.
   f. Water is an excellent solvent. **(Figure 2.5)**

2.3 Organic Molecular Structure of Living Systems

A. **Carbon**

1. Organic compounds contain carbon; most are produced in living systems.
2. Over one million carbon-based molecules have been identified.

B. **Carbohydrates: Nature's Most Abundant Organic Substance**

1. Carbohydrates contain carbon, hydrogen and oxygen, usually in ratio of 1C:2H:1O as H–C–OH.
2. Carbohydrates provide structural elements and store energy.
3. **Glucose** is commonly found in the blood of animals and is an important immediate energy source for cells. **(Figure 2.6, 2.7)**
4. **Cellulose** occurs in greater quantities than all other organic materials combined.
5. Carbohydrates, synthesized by plants by photosynthesis, are the starting point of food chains.
6. **Monosaccharides**
   a. Monosaccharides are simple sugars with a carbon backbone of four, five or six carbon atoms.
   b. Glucose, galactose and fructose all contain free sugar groups. **(Figure 2.8)**
   c. The hexose glucose is particularly important in life.
7. **Disaccharides (Figures 2.9)**
   a. Disaccharides contain two monosaccharides bonded together.
   b. Maltose is formed from binding two glucose molecules and removing one water molecule.
   c. Sucrose (table sugar) is a linkage of glucose to fructose.
   d. Lactose (milk sugar) is a linkage of glucose and galactose.
8. **Polysaccharides**
   a. Polysaccharides are chains of glucose molecules called polymers.
   b. Most have the formula $(C_6H_{10}O_5)n$ where *n* is the number of simple sugar subunits.
   c. Glycogen is a polymer of glucose; found in vertebrate liver and muscle cells, it is storage carbohydrate of animals.
   d. Cellulose is the principal structural carbohydrate of plants.

C. **Lipids: Fuel Storage and Building Material**

1. Lipids are fats and fat-like substances.
2. Lipids have low polarity; therefore they are insoluble in water but soluble in organic solvents.
3. **Triglycerides (Figure 2.10)**
   a. Stored fats are derived directly or converted from carbohydrates; they are the major animal fuels.
   b. **Triglycerides** consist of glycerol and three molecules of fatty acids.

c. Neutral fats are esters, combining alcohol and an acid.
d. Fatty acids in triglycerides are usually 14–24 carbons long.
e. When every carbon in a chain is bonded to two hydrogen atoms, it is **saturated**.
f. **Unsaturated** fatty acids, common in plant oils, have two or more carbon atoms joined by double bonds. **(Figure 2.11)**

4. **Phospholipids (Figure 2.12)**
   a. Phospholipids have a structural role in molecular organization of tissues and membranes.
   b. They resemble triglycerides with one fatty acid replaced by phosphoric acid and an organic base.
   c. **Lecithin** is an important phospholipid of nerve membranes.
   d. The phosphate group is charged and therefore polar; the rest of the molecule is nonpolar, so phospholipids can bridge both environments.
   e. The term **amphiphilic** describes compounds, like phospholipids, that are polar and water-soluble on one end and non-polar on the other end.
5. **Steroids (Figure 2.13)**
   a. Steroids are complex alcohols with fat-like properties.
   b. They are biologically important.
   c. Steroids include cholesterol, vitamin D, adrenocortical hormones and sex hormones.

D. **Amino Acids and Proteins**
1. **Proteins** are large molecules composed of 20 kinds of **amino acids**. **(Figure 2.14)**
2. Amino acids are joined by peptide bonds.
3. Two amino acids and a peptide bond form a **dipeptide**.
4. With one free amino group on one end and a free carboxyl on the other, additional amino acids can be joined to form a long chain of enormous variety.
5. Levels of Protein Structure (**Figure 2.15)**
   a. **Primary structure** is the sequence of amino acids in the polypeptide chain.
   b. **Secondary structure** comes from the bond angles of the sequence: alpha-helix and beta sheets.
   c. Bending and folding of secondary structures forms the **tertiary structure**, often stabilized by disulfide, hydrogen, ionic and hydrophobic bonds.
   d. Quaternary structure occurs when several polypeptide chains form subunits of a huge protein molecule, as in hemoglobin.
6. Proteins form much of the framework of the cytoplasm and organelles.
7. Proteins function as enzymes to catalyze most reactions; cell biology can be studied as protein biology.
8. Prions are infectious proteins that cause the host’s normal proteins to become contorted into abnormal 3-dimensional shapes.

E. **Nucleic Acids**
1. Nucleic acids are complex polymeric molecules.
2. Sequence of nitrogenous bases encodes genetic information for inheritance.
3. They store directions for synthesis of enzymes and other proteins.
4. They are the only molecules that can replicate themselves.
5. DNA is deoxyribonucleic acid.
6. RNA is ribonucleic acid.
7. Both DNA and RNA are polymers of repeated units called nucleotides, each containing a sugar, a nitrogenous base and a phosphate group.

2.4. Chemical Evolution

A. **Oparin-Haldane Hypothesis**
1. Aleksander Oparin and J.B.S. Haldane independently proposed a hypothesis of chemical evolution.
2. They proposed the early atmosphere consisted of simple compounds: water, carbon dioxide, hydrogen gas, methane and ammonia, but lacked oxygen.
3. The compounds necessary for life are not synthesized outside cells nor are they stable in the presence of oxygen.
4. Rock evidence indicates virtually no atmospheric oxygen at earliest times; this provided a reducing atmosphere.

5. Both methane (CH_4) and ammonia (NH_3) are fully reduced compounds.
6. Such an atmosphere, with variations in heat and high radiation, was conducive to prebiotic synthesis but unsuited to modern life forms.
7. Many chemicals would not react without a continuous source of free energy to produce a reaction.
8. Electrical discharges in lightning today produce a large amount of organic matter.
9. Alternative to the "hot dilute soup" scenario is the hydrothermal vent hypothesis, which places these extreme events underwater.

B. **Prebiotic Synthesis of Small Organic Molecules (Figure 2.16)**

1. In 1953, Stanley Miller and Harold Urey tested the Oparin-Haldane hypothesis.
2. A mixture of methane, hydrogen, ammonia, and water was circulated past an electric spark, boiled, and condensed; after a week of continuous sparking, approximately 15% of the carbon had been converted to organic compounds.
3. Many compounds related to life were formed, including four of the amino acids, urea and several simple fatty acids.
4. Critics contend that the early earth atmosphere may have been different from Miller's test.
5. Omitting ammonia and methane resulted in smaller amounts of compounds and required longer time periods.
6. More recent experiments have clarified the sequences leading through formaldehyde, hydrogen cyanide, cyanoacetylene, etc. that react with water and ammonia or nitrogen to produce a wider array of organic compounds.
7. The finding of amino acids in meteorites provides additional evidence for their natural abiotic synthesis.

C. **Formation of Polymers**

1. The next state required condensation of amino acids, nitrogenous bases and sugars.
2. These polymerizations are condensation (dehydration) reactions
3. Water tends to drive reactions toward decomposition by hydrolysis.
4. In living systems, condensation reactions occur in aqueous (cellular) environments with enzymes.
5. Without enzymes and ATP energy, macromolecules soon decompose.
6. The strongest hypothesis for prebiotic assembly of biologically important polymers is that they occurred within the boundaries of semi-permeable membranes formed from small amphiphilic molecules.
7. Amphiphiles extracted from the Murchison meteoriteform membranous vesicles in aqueous solutions (Figure 2.17); fatty acids and long-chained alcohols from meteorites may be possible components of prebiotic membranes.

2.5. Origin of Living Systems

A. **Self-replicating Systems**

1. Fossils date to 3.8 billion years ago; earliest life form probably originated 4 billion years ago.
2. **Protocells** would have been autonomous, membrane-bound units with functional organization that permitted self-reproduction.
3. On top of previous chemical evolution, nucleic acids were needed as simple genetic systems.
4. This causes a biological paradox.
   a. How could nucleic acids appear without the enzymes to synthesize them?
   b. How could enzymes evolve without nucleic acids to direct their synthesis?
5. Their RNA, not protein content, catalyzes translation of mRNA by ribosomes.
6. Therefore, earliest enzymes could have been RNA, which would have been the earliest self-replicating molecules; thus it would have been an "RNA world."
7. Proteins are better catalysts and DNA is more stable; thus they would eventually be selected.
8. Before this stage, only environmental conditions and chemistry shaped biogenesis.
9. After this stage, the system responds to natural selection and evolves.

B. **Origin of Metabolism (Figure 2.18)**

1. History of the evolution of complex metabolism is yet to be understood; a model is proposed here.
2. Autotrophs synthesize their own food; heterotrophs must obtain food from the environment.
3. Earliest microorganisms are considered primary heterotrophs; they were probably anaerobic and similar to *Clostridium* bacteria.
4. They could survive as long as the nutrient soup was abundant; protocells that converted inorganic precursors to a required nutrient would have a selective advantage as nutrients were depleted.

5. Evolution of autotrophic organisms required gaining enzymes to catalyze conversion of inorganic molecules to more complex ones.

C. **Appearance of Photosynthesis and Oxidative Metabolism**
1. **Autotrophy evolves with photosynthesis.**
2. Modern photosynthesis involves carbon dioxide and water to form sugar and oxygen.
3. Early photosynthesis probably used hydrogen sulfide or other hydrogen sources.
4. Production of oxygen began building an atmosphere; at 1% of its current level, oxygen begins to form an ozone shield and restrict UV radiation reaching the surface.
5. Then photosynthetic organisms spread across land and water, increasing oxygen production.
6. Oxidative (aerobic) metabolism appeared using oxygen as the terminal receptor and completely oxidizing glucose to carbon dioxide and water.
7. Cyanobacteria, eukaryotic algae and plants have generated our current atmosphere of 21% oxygen.

2.6. Precambrian Life

A. **Cambrian Explosion**
1. Pre-Cambrian covers time before Cambrian began nearly 600 million years ago.
2. Most animal phyla appear within a few million years at the beginning of Cambrian: the "**Cambrian explosion**."
3. This likely represents the absence of fossilization rather than abrupt emergence.

B. **Prokaryotes and the Age of Cyanobacteria (Blue-Green Algae)**
1. Primitive Structures of Prokaryotes
   a. A single DNA molecule, lacking histones, is in a nucleoid but not bound by nuclear membranes.
   b. They lack mitochondria, plastids, Golgi apparatus and endoplasmic reticulum.
   c. During division, the nucleoid divides and replicates but does not go through organized mitosis.
   d. Cyanobacteria peaked in abundance one billion years ago; they were dominant for two-thirds of life's history.
2. They are classified in kingdom Monera by some taxonomists, and kingdom Eubacteria by others.
3. Prokaryotes comprise two lineages of very distinct organisms.
   a. Most bacteria are in the kingdom Eubacteria.
   b. Archaebacteria have a unique cellular metabolism, different cell wall chemistry and unique ribosomal RNA.

C. **Appearance of Eukaryotes (Figure 2.19)**
1. Advanced Structures of Eukaryotes
   a. A membrane nucleus contains chromosomes composed of chromatin.
   b. There is more DNA, and eukaryotic chromatin contains histones and RNA.
   c. Cellular division usually is an organized process called mitosis.
   d. In the cytoplasm are many membrane-bound organelles.
2. Fossils suggest eukaryotes arose 1.5 million years ago. **(Figure 2.20)**
3. Lynn Margulis and others proposed eukaryotes are a symbiosis of multiple bacteria. **(Figure 2.21)**
   a. Mitochondria and plastids contain their own DNA.
   b. Nuclear, plastid and mitochondrial ribosomal RNAs show distinct evolutionary lineages.
   c. Plastid and mitochondrial ribosomal DNA is closer to bacterial DNA.
   d. Plastids are closest to cyanobacteria in structure and function.
   e. A host cell that could incorporate plastids or mitochondria with their enzymatic abilities would be at a great advantage.
4. Endosymbiotic theory proposes that pre-eukaryotes arose from anaerobic bacteria that served as a host with aerobic bacteria. **(Figure 2.22)**
   a. The nucleus and other organelles were derived from infoldings of the cell membrane.
   b. Aerobic bacteria were ingested or parasitized and came to reside in the cytoplasm.
   c. A permanent mutualistic relationship developed whereby the aerobic bacteria living in its host would have metabolized toxic oxygen and the host anaerobic bacteria provided food and protection.
   d. Scientists have collected data and tested this theory and found that it is a reasonable.
5. Eukaryotes may have originated many times.
6. Heterotrophs that cropped cyanobacteria provided ecological space for other types of organisms.

7. Food chains of producers, herbivores and carnivores accompanied a burst of evolutionary activity that may have been permitted by atmospheric changes.
8. The merging of disparate organisms to produce evolutionary novel forms is called symbiogenesis.

Lecture Enrichment

1. Some substances have macroscopic images (e.g., sugar, lipids, protein in meat) and the large size of an albumin molecule is apparent in the thick viscosity of egg white, but it is difficult to image something that is primarily nucleic acid, etc. without lab work.
2. Note how different molecules such as nucleic acids and proteins may appear different in various life forms but still have the same basic structure to perform the same kind of job. Why are some molecules essentially the same in bacteria and humans and very different in others?
3. Draw, use transparencies, slides or video to illustrate the different isomeric forms of the hexose sugars glucose, fructose, and galactose, and reasons for their different characteristics. Show how the structures fit into enzymes and why different enzymes would be needed to interact with different isomers.
4. Speculate what would happen if genetic engineering gave humans the ability to directly digest cellulose. Would this be useful or not? Ask students to consider the structure of our digestive tracts and the current use of cellulose as roughage.
5. Describe how denaturation affects the different levels of a protein’s structure. Which levels would be most affected by denaturation? Contrast denaturation caused by heat (cooking food) as opposed to mild denaturation caused by reversible pH changes.
6. Compare the bonds that link the carbohydrates, lipids, proteins and nucleic acids. Consider the size of the final molecules and which ones are branched and unbranched. Prepare students for the link between the information in DNA, RNA and proteins that will be discussed later.
7. Early researchers probing the possibility of life on other planets speculated that it might be based on another atom besides carbon—perhaps silicon. Ask students to consider the chemical properties of silicon compared to carbon and speculate on how this might make life different or impossible as we know it.

Commentary/Lesson Plan

Background: There is substantial chemical knowledge assumed in this chapter, including references to rather remote properties of clay soil and microspheres. Most discussion of basic carbohydrates, lipids and proteins should constitute review from previous biology coursework in high school and college.
Misconceptions: Students may assume that most major breakthroughs are made by the U.S. science establishment; both J.B.S. Haldane (British) and Aleksander Oparin (Russian) were not Americans. How we view the world determines what we believe and what we believe determines how we view the world; thus anti-evolutionists focus on detecting contradictions and paradoxes in evolutionary theory, but the ribozyme/RNA world discovery demonstrates how some logical dilemmas resolve themselves. Students often only relate “polymer” with plastic, but the monomer-polymer concept for cellulose, chitin, etc. is equivalent. Many students will find it “intuitive” that the first cells had to be autotrophic.
Schedule: The speed of coverage of this chapter will vary considerably depending on the general chemistry background of students. Some understanding of basic chemistry is critical to appreciating the roles of organelles in the next chapter.

HOUR 1 2.1. Spontaneous Generation of Life
- A. History

2.2. Organic Molecular Structure of Living Systems
- A. Carbon
- B. Carbohydrates
- C. Lipids
- D. Amino Acids and Proteins
- E. Nucleic Acids

HOUR 2 2.3. Chemical Evolution
- A. Oparin-Haldane Hypothesis
- B. Prebiotic Synthesis of Small Organic Molecules
- C. Formation of Polymers

2.4. Origin of Living Systems
- A. Self-replicating Systems
- B. Origin of Metabolism
- C. Appearance of Photosynthesis and Oxidative Metabolism

2.5. Precambrian Life
- A. Cambrian Explosion
- B. Prokaryotes and the Age of Cyanobacteria (Blue-Green Algae)
- C. Appearance of the Eukaryotes

2.6. A. Symbiogenesis

ADVANCED CLASS QUESTIONS:

1. The atoms and bonds within a molecule determine its chemical and physical properties. Compare fats that contain mostly saturated fatty acids with oils that contain mostly unsaturated fatty acids to demonstrate this concept.
2. The properties of a molecule determine the role that the molecule plays in the cells or the body of an organism. Why are phospholipids useful in membranes?
3. Ask why life is based on carbon. Note the characteristics of carbon that could be responsible for this usage. Ask students to speculate why silicon, with four electrons in its outer shell, would function as the basis of life.
4. Query how the amount of ATP used in one day can exceed by many times the amount of ATP in the human body.
5. Ask if condensation and hydrolysis reactions would be exact opposites of each other. Point out that these reactions are not generally one-step processes, but require several steps and several enzymes to carry out the complete reaction.
6. Discovery of liquid water under the frozen surface of a distant moon in our solar system has caused scientists to speculate on the possibility of life on that moon. Researchers hold little hope of any familiar life form existing on any planet or moon in the absence of water. Why?
7. Life has a chemical and physical basis. Give an example from your knowledge of nutrition, medicine or the environment to show that this concept has everyday applications.
8. Atomic structure involves electronic energy levels. Show that living things are dependent upon the energy relationships of electrons.
9. So far, for every molecule that life forms can put together, such as cellulose or chitin, there are bacteria that can digest them into sugar and other smaller molecules. What would happen if a tree or insect could build a complex molecule that no organism or natural process could decompose?
10. Many insects feed exclusively on one type of food such as plant sap (primarily sugar), blood proteins or starch. Yet these organisms are themselves made of a wide range of molecules. Where does this molecular diversity come from?