Chapter 3: Lecture Notes

Introduction

- In 1984 a Martian rock was found in Antarctica.
- ALH 84001, as the meteorite is now called, was determined to be 4.5 billion years old and to have landed on Earth's surface about 11,000 years ago.
- Water, the prerequisite for life as we know it, was discovered beneath the surface of the meteorite.
- This discovery caused scientists to wonder if ALH 84001 might contain other signs of life.
- Further analysis of the meteorite revealed two substances related to life:
  - Simple carbon-containing molecules called polycyclic aromatic hydrocarbons
  - Crystals of magnetite, an iron oxide mineral made by many living things on Earth
- Fragments of another meteorite that fell in Australia in 1969 contained the building blocks of both DNA and protein.
- These findings suggest that life may not be unique to Earth.
- This chapter presents two hypotheses for the origin of life on Earth and looks at the four macromolecules that characterize living organisms: proteins, carbohydrates, lipids, and nucleic acids.

Theories of the Origin of Life

- Living things are composed of the same elements as the inanimate universe.
- The arrangement of these elements in biological systems is unique.
- There are two theories for the origin of life during the 600 million years of the Hadean:
  - Life from extraterrestrial sources
  - Chemical evolution

Could life have come from outside Earth?

- Along with the possibility that comets brought Earth most of its water (Chapter 2), the composition of meteorites suggests that some of life's complex molecules could have come from space.
- There is no proof, however, that living things have ever traveled to Earth by way of a comet or meteorite.
- Scientists have traditionally found it hard to believe that an organism in a meteorite could survive thousands of years of traveling through space, followed by the intense heat generated as it passed through Earth's atmosphere.
- However, recent evidence suggests that the heat inside meteorites may not have been severe.
  - By carefully measuring the extent of magnetic field reorientation in ALH 84001, scientists at the California Institute of Technology have concluded that the inside of the meteorite was never hotter than 40°C.

Did life originate on Earth?

- The theory of chemical evolution holds that conditions on primitive Earth led to the formation of the large molecules unique to life.
- In the 1950s, Stanley Miller and Harold Urey set up an experimental "primitive" atmosphere containing hydrogen gas, ammonia, methane gas, and water vapor.
  - A spark was passed through these gases to simulate lightning and the system was cooled to allow the gases to condense in a watery solution, or "ocean." (See Figure 3.1. and Animated Tutorial 3.1.)
  - Within days, the system contained numerous complex molecules, including amino acids, purines, and pyrimidines.
- The results of the Miller-Urey experiments have undergone several interpretative refinements.
  - The amino acids present in living organisms all exist in the L-configuration. (see Figure 2.21.)
  - The amino acids formed in the Miller-Urey experiments were mixtures of the D- and L-forms.
  - Recent experiments show that rocks present in abundance during the Archean had unique crystal structures that could have bound selectively to D- or L-amino acids, separating the two.
  - Scientists now believe Earth's original atmosphere contained CO_2, N_2, H_2S, and SO_2 in addition to those chemicals used in the Miller-Urey experiments.
  - The inclusion of these molecules in experiments with prebiotic "soup" could have led to the formation of more diverse molecules.
  - Scientists have determined that solid mineral surfaces, such as finely divided clays, seem to provide the best environment to bind monomers and allow them to polymerize.
  - Scientists have proposed that extreme environments—found beneath ice, in deep-sea hydrothermal vents, and within fine clays near the shore—could be the original site of life's emergence.

- The earliest stages of chemical evolution resulted in the emergence of monomers and polymers that probably have remained generally unchanged for 3.8 billion years.

Macromolecules: Giant Polymers

- There are four major types of biological macromolecules: proteins, carbohydrates, lipids, and nucleic acids.
- These macromolecules are made the same way in all living things, and they are present in all organisms in roughly the same proportions. (See Figure 3.2.)
- An advantage of this biochemical unity is that organisms acquire needed biochemicals by eating other organisms.
- Macromolecules are giant polymers. *Poly* means many; *mer* means units.
- Polymers are formed by covalent linkages of smaller units called monomers; *mono* means single. (See Table 3.1.)
- Molecules with molecular weights greater than 1,000 daltons (atomic mass units) are usually classified as macromolecules.
- Some of the roles of macromolecules are:
  - Energy storage
  - Structural support
  - Catalysis
  - Transport
  - Protection and defense
  - Regulation of metabolic activities
  - Maintenance of homeostasis
  - Means for movement, growth, and development
  - Heredity
- The functions of macromolecules are related to their shape and the chemical properties of their monomers. (See Animated Tutorial 3.2.)
- Proteins can fold to create complex functional structures such as catalysts or strong, flexible fibers like those found in spider webs.
- Carbohydrates (sugars) link to form cellulose, the wood fiber of trees, or starches for storing energy.
- Proteins can form long, thin assemblies that can contract and cause movement.
- Some types of macromolecules contain many different kinds of monomers.
- Some contain the same simple units, repeated many times.

Condensation and Hydrolysis Reactions

- Macromolecules are made from smaller monomers by means of a condensation or dehydration (loss of water) reaction in which an OH from one monomer is linked to an H from another monomer. (See Figure 3.3*a*.)
- Energy must be added to make or break a polymer.
- The reverse reaction, in which polymers are broken back into monomers, is a called a hydrolysis reaction (*hydro* means water; *lysis*, break). (See Figure 3.3*b*.)
- In a hydrolysis reaction, water reacts with the bonds that link the units together.
- *Special proteins, called enzymes, are needed to make polymers from monomers.*
- *Most hydrolysis in biological systems is also performed by enzymes, although a strong acid or base solution can hydrolyze many types of polymers.*
- *In people, stomach acid hydrolyzes some of the linkages found in the polymers we eat.*

Proteins: Polymers of Amino Acids

- Proteins are molecules with diverse structures and functions.
- Proteins have important roles in:
  - Structural support
  - Protection
  - Catalysis
  - Transport
  - Defense
  - Regulation
  - Movement
- Proteins called enzymes are particularly important in biological systems. Enzymes increase the rates of chemical reactions in cells, a function known as catalysis.
- Enzymes are highly specific; in general, each enzyme catalyzes only one chemical reaction.

- Proteins range in size from a few amino acids to thousands of them.
  - Some proteins are composed of a single chain of amino acids, called a polypeptide.
  - Other proteins have more than one polypeptide chain.
- Folding is crucial to the function of a protein and is influenced largely by the sequence of amino acids.
- Each different type of protein has a characteristic amino acid composition and order.

Proteins are composed of amino acids

- The amino group is the nitrogen-containing part (NH_3^+).
- The acid is a carboxyl group (COO^-).
- Differences in amino acids come from the side chains, or the R groups, found attached to the same carbon as the amino group. (See Table 3.2.)
- The 20 common amino acids vary widely in properties.
- All but one have four different groups that are attached to the α carbon.
  - A hydrogen atom, an amino group, and a carboxyl group are bonded to the α carbon of all the different amino acids.
  - The fourth group, the R group, is what makes one type of amino acid different from another.
  - Glycine has H as its R group and therefore is the only amino acid that has three, rather than four, groups attached to the α carbon.
  - *Carbons with four different groups (that is, all of them except for glycine) can exist in different stereoisomeric forms.*
- Amino acids can be classified based on the characteristics of their R groups.
  - Five of the 20 amino acids have charged hydrophilic side chains.
  - Five of the 20 have polar but uncharged side chains.
  - Seven of the 20 have nonpolar hydrophobic side chains.
- Three amino acids—cysteine, glycine, and proline—have some special properties.
  - Cysteine has a terminal disulfide (—S—S—). (See Figure 3.4.)
  - Glycine has a hydrogen atom as the side chain. This group is small enough to fit into small spaces and tight corners when the protein folds.
  - Proline has a modified amino group that forms a covalent bond with the R group.
    - Proline's ring limits rotation of the α carbon's bond.
    - Proline is often found at bends and loops of proteins.

Peptide linkages covalently bond amino acids together

- Proteins are synthesized by condensation reactions between the amino group of one amino acid and the carboxyl group of another. This forms a peptide linkage. (See Figure 3.5.)
- Proteins are also called polypeptides. A dipeptide is two amino acids long; a tripeptide, three. A polypeptide is multiple amino acids long.
- The first amino acid of a peptide is called the N-terminus amino acid because the amino group is free, or unbound.
- The last amino acid of a peptide is called the C-terminus amino acid and has a free carboxyl group.
- The C—N peptide linkage forms a partial double bond, which is a single covalent and polar attraction. This bond limits folding and restricts the ability of the adjacent atoms to rotate.
- Within the central axis of the protein, there is an asymmetry of charge favoring a tendency toward hydrogen bonding. (Oxygen is partially negative and nitrogen is slightly positive.)

The primary structure of a protein is its amino acid sequence.

- There are four levels of protein structure: primary, secondary, tertiary, and quaternary. (See Figure 3.6.)
- The precise sequence of amino acids is called its primary structure.
- The peptide backbone consists of repeating units of atoms: N—C—C—N—C—C.
  - In Figure 3.5, the portion on the left is the N terminus; the portion on the right is the C terminus.
  - The protein is synthesized by the addition of monomers joined by peptide linkages between the N terminus of one monomer and the C terminus of another.
- Many proteins have now been sequenced.
  - There are two conventions for representing the sequence: the three-letter and one-letter systems. (See Table 3.2.)
  - *In the three-letter system, methionine is* Met*; in the one-letter system, it is* M.
- Enormous numbers of different proteins are possible.
  - With 20 amino acids, 400 different dipeptides are possible ($20 \times 20 = 400$).

- There are 20^{100} different possible proteins that are made up of just 100 amino acids. Proteins can also be made up of fewer or more than 100 amino acids, which makes the number of different proteins mind-boggling.

The secondary structure of a protein requires hydrogen bonding

- A protein's secondary structure consists of the regular, repeated patterns in different regions in the polypeptide chain.
- This shape is influenced primarily by hydrogen bonds arising from the amino acid sequence (the primary structure).
- There are two common secondary structures, the α helix and the β pleated sheet.
  - The α helix is a right-handed coil. (See Figure 3.6b.)
    - The peptide backbone takes on the helical shape due to hydrogen bonds.
    - The R groups point away from the peptide backbone.
    - Large R groups tend to prevent the creation of this structure.
  - Insoluble fibrous structural proteins have α-helical secondary structures. Examples are the proteins found in hair, feathers, and hooves, which are called keratins.
    - Hair stretches because only hydrogen bonds, not covalent bonds, are broken when it is pulled.
    - β pleated sheets form from peptide regions that lie parallel to each other. (See Figure 3.6c.)
    - Sometimes the parallel regions are in the same peptide.
    - Sometimes the parallel regions are from different peptide strands.
    - This sheetlike structure is stabilized by hydrogen bonds between N—H groups on one chain with the C=O group on the other.
    - Spider silk is made of β pleated sheets from separate peptides. Despite the weakness of the hydrogen bonds, their strength tends to be additive; therefore, substances like spider silk can be remarkably strong.

The tertiary structure of a protein is formed by bending and folding

- Tertiary structure is the three-dimensional shape of the completed polypeptide. (See Figure 3.6d.)
- The primary determinant of the tertiary structure is the interaction between R groups.
- Other factors are:
  - The nature and location of secondary structures
  - The location of disulfide bridges, which form between cysteine residues
  - Hydrophobic side-chain aggregation and van der Waals forces, which help stabilize them
  - The ionic interactions between the positive and negative charges deep in the protein, away from water
- A complete description of a protein's tertiary structure specifies the location of every atom in the molecule in three-dimensional space. (See Figure 3.7.)
- (See Video 3.1.)

The quaternary structure of a protein consists of subunits

- Some proteins are composed of subunits, separate peptide chains that associate together to create the functional protein. (See Figure 3.6e.)
  - This level of structure is called the quaternary structure, and it adds to the three-dimensional shape of the finished protein.
- Quaternary structure results from the ways in which multiple polypeptide subunits bind together and interact.
- Hemoglobin is an example of such a protein; it has four subunits. (See Figure 3.8.)
- (See Video 3.2.)

The surfaces of proteins have specific shapes

- Shape is crucial to the functioning of some proteins, as in the following examples:
  - Enzymes need certain surface shapes in order to bind substrates correctly.
  - Carrier proteins in the cell surface membrane allow substances to enter the cell.
  - Chemical signals such as hormones bind to proteins on the cell surface membrane.
- Cells in tissues snap together and are held by the complementary shapes.
- Multicomponent proteins are held together by their shape, charges, hydrophobic properties, and occasionally by disulfide bonds.
- The combination of attractions, repulsions, and interactions determines the right fit. (See Figure 3.9.)
- Knowing the exact shape of a protein and what can bind to it can be important in fields such as medicine. For example, HIV patients are treated with protease inhibitors designed to bind to and block the action of the viral protease. (See Figure 3.10.)

Protein shapes are sensitive to the environment

- Changes in temperature, pH, salt concentrations, and oxidation or reduction conditions can change the shape of proteins. This loss of a protein's normal three-dimensional structure is called denaturation. (See Figure 3.11.)
- Often denaturation is irreversible, as in the boiling of egg white.
- Some chemically induced changes are reversed by removal of the chemical condition that caused them.
- *A few proteins, like ribonuclease, resist denaturation; they can be boiled for days and retain activity once cooled.*

Chaperonins help shape proteins

- When a protein fails to fold correctly, serious complications can occur. In Alzheimer's disease, misfolded proteins accumulate in the brain and bind to one another, forming fibers in the areas of the brain that control memory, mood, and spatial awareness.
- Chaperonins are specialized proteins that help keep other proteins from interacting inappropriately with one another prior to positioning.
- Some chaperonins help folding; some prevent folding until the appropriate time. (See Figure 3.12.)

Carbohydrates: Sugars and Sugar Polymers

- Carbohydrates are carbon molecules with hydrogen and hydroxyl groups.
  - They act as energy storage and transport molecules.
  - They also serve as structural components.
- Polymers composed of monomers can have molecular weights of up to hundreds of thousands of daltons.
- There are four major categories of carbohydrates:
  - Monosaccharides
  - Disaccharides, which consist of two monosaccharides
  - Oligosaccharides, which consist of between 3 and 20 monosaccharides
  - Polysaccharides, which are composed of hundreds to hundreds of thousands of monosaccharides
- The general formula for a carbohydrate monomer is multiples of CH_2O, maintaining a ratio of 1 carbon to 2 hydrogens to 1 oxygen.
- During the polymerization, which is a condensation reaction, water is removed. As a result, the carbohydrate polymers have ratios of carbon, hydrogen, and oxygen that differ somewhat from the 1:2:1 ratios of the monomers.

Monosaccharides are simple sugars

- All living cells contain glucose ($C_6H_{12}O_6$).
- Green plants produce monosaccharides; other organisms acquire glucose, or the energy to make it, from plants.
- Cells break down glucose to release energy, with the final products being carbon dioxide and water.
- Glucose exists as a straight chain and a ring. (See Figure 3.13.)
  - The ring form is predominant (>99%).
  - The two forms of the ring, α-glucose and β-glucose, exist in equilibrium when dissolved in water.
- Different monosaccharides have either different numbers or different arrangements of carbons. (See Figure 3.14.)
  - Most monosaccharides are optical isomers.
  - Hexoses (six-carbon sugars) include the following structural isomers: glucose, fructose, mannose, and galactose.
  - Two examples of pentoses (five-carbon sugars) are ribose and deoxyribose, which make up the backbones of nucleic acids (RNA and DNA).
  - These pentoses are not isomers. Deoxyribose lacks an oxygen atom at carbon 2. This results in a functional distinction between DNA and RNA.

Glycosidic linkages bond monosaccharides together

- Glycosidic linkages are created by enzymes and are condensation reactions.
- Disaccharides have just one such linkage.
  - Sucrose (table sugar) is glucose bonded to a fructose.
  - Lactose (milk sugar) is glucose bonded to a galactose.
  - Maltose has two α-linked glucose molecules. Cellobiose also has two glucose molecules, but they are β-linked.
- (See Figure 3.15.)
- Maltose and cellobiose have the same chemical formula but are structural isomers.
  - The shape difference changes the biological nature of the molecules.
  - Enzymes that break down maltose fail to break down cellobiose.
  - Humans can break down maltose, but not cellobiose.

- Oligosaccharides contain more than two monosaccharides.
  - Many proteins found on the outer surface of cells have oligosaccharides attached to the R group of certain amino acids, or to lipids.
  - The human ABO blood types owe their specificity to oligosaccharide chains.

Polysaccharides serve as energy stores or structural materials

- Polysaccharides are giant chains of monosaccharides connected by glycosidic linkages. (See Figure 3.16.)
- Cellulose is a giant polymer of glucose alone, joined by β-1,4 linkages. (See Figure 3.16*a*.)
- Starch is a polysaccharide of glucose with α-1,4 linkages.
- Starch can be degraded readily by the action of chemicals or enzymes, making it a good storage medium.
- Cellulose is much more stable chemically than starch and more difficult to hydrolyze chemically and enzymatically. This quality makes it an excellent structural material.
- Starches vary by amount of branching. (See Figure 3.16*b*.)
  - Some plant starch, such as amylose, is unbranched. Others, such as amylopectin, are moderately branched.
  - Animal starch, called glycogen, is a highly branched polysaccharide.
    - Glycogen stores glucose, which is needed for fuel.
    - Glucose must be stored as a polymer in order to reduce the osmotic pressure exerted in the cell; for example, 1,000 glucose molecules stored individually would exert the same osmotic pressure as one glycogen molecule.
    - Combining many glucose molecules into just one reduces the osmotic effect, allowing storage of lots of energy without disturbing the water content of a cell.
- (See Videos 3.3 and 3.4.)

Chemically modified carbohydrates contain other groups

- Carbohydrates are modified by the addition of functional groups. (See Figure 3.17.)
- Glucose can oxidize to acquire a carboxyl group (—COOH), producing glucuronic acid.
- Phosphate added enzymatically to one or more of the hydroxyl (—OH) sites creates a sugar phosphate such as fructose 1,6-bisphosphate.
- Amino groups can be substituted for an —OH, making an amino sugar such as glucosamine and galactosamine.
  - Amino sugars are important to the extracellular matrix, the system that holds tissues together.
  - Galactosamine is a major component of the cartilage found in ears, noses, and kneecaps.
  - A glucosamine derivative is a component of chitin, the polysaccharide in the skeletons of insects, prawns, and crabs. It is also found in the cell walls of fungi. Chitin is one of the most abundant substances on earth.

Lipids: Water-Insoluble Molecules

- *Life is cellular; the differences between what is outside and inside a cell define life.*
- *Biological molecules called lipids maintain these differences.*
- Lipids are diverse biological molecules that share a common chemical property: They are insoluble in water.
  - This insolubility results from the many nonpolar covalent bonds of hydrogen and carbon in lipids.
  - Lipids aggregate away from water, which is polar, and are attracted to each other via weak, but additive, van der Waals forces.
- Technically lipids are not polymers, because the subunits are not held together by covalent bonds, but they may be considered polymers of individual lipid units.
- The roles for lipids in organisms include energy storage (fats and oils), cell membranes (phospholipids), capture of light energy (carotinoids), hormones and vitamins (steroids and modified fatty acids), thermal insulation, electrical insulation of nerves, and water repellency (waxes and oils).

Fats and oils store energy

- Fats and oils are triglycerides, or simple lipids composed of three fatty acid molecules and one glycerol molecule. (See Figure 3.18.)
- Glycerol (or glycerin) is a three-carbon molecule with three hydroxyl (—OH) groups, one for each carbon.
  - Each —OH is the site where an enzyme adds a fatty acid.
- Fatty acids are long linear chains of hydrocarbons with a carboxyl group (—COOH) at one end. (See Figure 3.19.)
- In saturated fatty acids, the hydrocarbon chain has only single carbon-to-carbon bonds. Hydrogen atoms complete the valence requirements, thus saturating the chain.
  - Saturated fatty acids are rigid and straight, and they are solid or semisolid at room temperature. (See Figure 3.19*a*.)

  - Animal fats are saturated.
- Unsaturated fatty acids are those that have at least one double-bonded carbon in one of the hydrocarbon chains. At these positions, there are two fewer hydrogen atoms—the chain is not completely saturated with hydrogen atoms.
  - The double bonds in unsaturated fatty acids cause rigid kinks that prevent easy packing. As a result, unsaturated fatty acids are liquid at room temperature. (See Figure 3.19*b*.)
  - Plants commonly have short and/or unsaturated fatty acids that tend to be more fluid than those of animal fats, even at cold temperatures.
- Fats and oils are marvelous storehouses for energy and are used by animals and plants for fuel compounds in metabolism.
- (See Video 3.5.)

Phospholipids form the core of biological membranes

- Lipids do not normally interact with water or with the many biologically important substances that are soluble in water.
- Thus lipids play a crucial role in living cells—separating regions with different concentrations of ions and other chemicals.
- Phospholipids have two hydrophobic ("water-hating") fatty acid tails and one hydrophilic ("water-loving") phosphate attached to the glycerol. (See Figure 3.20.)
- As a result of this structure, phospholipids orient themselves so that the phosphate group faces water and the tail faces away from water.
- In aqueous environments, these lipids form bilayers, with heads facing outward, and tails facing inward. (See Figure 3.21.)
- Cell membranes are structured this way.

Carotenoids and steroids

- Carotenoids and steroids are specialized lipids with chemical structures that are very different from those of triglycerides and phospholipids.
- Carotenoids trap light energy.
  - Carotenoids are light-absorbing pigments found in plants and animals.
  - One, β-carotene, is a plant pigment used to trap light in photosynthesis. In animals, this pigment, when broken into two identical pieces of vitamin A, is required for vision. (See Figure 3.22.)
- Steroids are signaling molecules.
  - Steroids are organic compounds with a series of fused rings. (See Figure 3.23.)
  - The steroid cholesterol is a common part of animal cell membranes.
    - Cholesterol is absorbed from food and synthesized in the liver.
    - In addition to being a membrane constituent, it also is an initial substrate for synthesis of the hormones testosterone and estrogen.

Some lipids are vitamins

- Vitamins are small organic molecules essential to health.
- Vitamin A, for example, is made from β-carotene. It is important for normal development, maintenance of cells, and night vision. (See Figure 3.22.)
- Vitamin D is important for absorption of calcium in the intestines.
- Vitamin E, an antioxidant, protects membranes.
- Vitamin K is a component required for normal blood clotting.

Wax coatings repel water

- Waxes are highly nonpolar molecules. They protect our hair, birds' feathers, and insects' eggs from both the damaging effects of excess water and the damaging effects of water loss.
- Waxes are saturated long fatty acids bonded to long fatty alcohols via an ester linkage.
- A fatty alcohol is similar to a fatty acid except for the last carbon, which has a hydroxyl group (—OH) instead of a carboxyl group (—COOH).

Nucleic Acids: Informational Macromolecules That Can Be Catalytic

- Nucleic acid polymers are linearly arranged information molecules.
- Two types of nucleic acid polymers are DNA (deoxyribonucleic acid) and RNA (ribonucleic acid).
- The DNA molecules of humans are enormous polymers that encode hereditary information bound in nucleotides.

- *More than 130 million nucleotides are found in just one human chromosome of average length.*
- In nonreproductive cell activities, information stored in DNA is transferred to RNA molecules.
  - *The average RNA molecule, although occasionally thousands of bases in length, is much shorter than a DNA molecule.*
  - A DNA molecule contains information necessary for the production of many different RNA molecules. DNA molecules can code for RNA molecules repeatedly over the life of a cell.
  - The information in RNA molecules is decoded to specify the sequence of amino acids in proteins.
- Certain RNAs act as catalysts for important reactions in cells.

The nucleic acids have characteristic chemical properties

- Nucleic acids are composed of monomers called nucleotides. (See Figure 3.24.)
- The pentoses that form part of the backbones of DNA and RNA differ in one important respect: deoxyribose (found in DNA) is missing an oxygen from carbon 2 that is present in ribose (found in RNA).
- DNA typically is double-stranded: Two separate polymer chains are associated together. The association is not haphazard, but complementary.
  - At each position where a purine is found on one strand, a pyrimidine is found on the other.
  - Purines have a fused double-ring structure.
  - Pyrimidines have just one ring.
  - Pairing of a purine with a pyrimidine maintains three rings in the center of the molecule, so the backbones of the two strands maintain a constant distance along the length of the double-stranded molecule.
- DNA and RNA polymers are enzymatically made, and like all the other polymers mentioned so far, they are created with condensation reactions.
- The linkages that hold the nucleotides in the polymer are called phosphodiester linkages. (See Figure 3.25.)
- These linkages are formed between carbon 3 of the sugar (ribose in RNA, deoxyribose in DNA) and a phosphate group that is associated with carbon 5 of the sugar.
- The backbone consists of alternating sugars and phosphates.
- In DNA, the two strands are antiparallel: At one end, one strand ends with a free carbon 5′ of the deoxyribose, the other with a carbon 3′ of the deoxyribose.
- The two strands are held together by the attractions formed by nitrogenous bases in the center of the double-stranded molecule.
- The attractions are hydrogen bonds that form due to partial positive and negative charges, as described in Chapter 2.
- Most RNA molecules consist of only a single polynucleotide chain.

The uniqueness of a nucleic acid resides in its nucleotide sequence

- The main principle is complementary base pairing by hydrogen bond formation.
  - Only four different DNA bases are found in DNA: adenine (A), cytosine (C), guanine (G), and thymine (T).
  - Where an A is found on one strand, a T is found at the same point in the complementary strand.
  - Wherever a G is found on one strand, a C is found on the other.
  - Hydrogen bonds form between these bases, linking the two complementary strands.
  - DNA complementary strands form a double helix, a molecule with a right-hand twist.
- DNA is an *information molecule* and serves no other purpose. The information is stored in the *order* of the four different bases.
- This order is transferred to RNA molecules, which are used to direct the order of the amino acids in proteins.
- There are three main structural differences between DNA and RNA:
  - RNA has ribose, which has an oxygen at carbon 2 of the sugar.
  - RNA molecules have uracil instead of thymine. (See Table 3.3.)
  - RNA is generally single-stranded.
- Complementary hydrogen bonding between ribonucleotides in RNA can result in complex three-dimensional shapes important in determining associations between RNA molecules during protein synthesis. (See Figure 3.26.)
- DNA molecules have a much more uniform shape than the proteins they code for. (See Figure 3.27.) The uniform shape of DNA molecules makes the information they contain easy to “read.” This information is used to make a multitude of proteins, whose functions are related to their diverse shapes.
- (See Video 3.6.)

DNA is a guide to evolutionary relationships

- Closely related living species have DNA base sequences that are more similar than distantly related species.

- The comparative study of base sequences has confirmed many of the more traditional classifications of organisms based on body structure and biochemical similarities.
- For example, based on anatomical evidence, our closest living relatives are chimpanzees. DNA comparisons confirm this: We share more than 98 percent of our DNA base sequences with chimpanzees.
- One surprising discovery that has been made using this technique is that starlings (*Sturnus* sp.) are closely related to mockingbirds (*Mimus* sp.).

RNA may have been the first biological catalyst

- Certain RNA molecules called ribozymes can act as catalysts, using their three-dimensional shapes and other chemical properties.
- The discovery of ribozymes had important implications for theories of the origin of life. They provided a solution to the question of whether proteins or nucleic acids came first when life originated.
- Scientists now hypothesize that early life was part of an "RNA world."
- Since RNA can be informational and catalytic, it could have acted as a catalyst for its own replication as well as for the synthesis of proteins.
- Eventually DNA could have evolved by being made from RNA. There is some laboratory evidence supporting this scenario.
  - RNAs of different sequences have been put in a test tube and made to replicate on their own.
  - Ribozymes catalyze the formation of peptide linkages in living organisms today.
  - Retroviruses have an enzyme called reverse transcriptase that catalyzes the synthesis of DNA from RNA.

Nucleotides have other important roles

- *Some RNA monomers have important roles in energy transfer within cells.*
- The ribonucleotide ATP acts as an energy transducer in many biochemical reactions. It is the "cash" form of cellular energy. (See Chapter 6.)
- The ribonucleotide GTP powers protein synthesis. (See Chapters 12 and 15.)
- cAMP (cyclic AMP) is a special ribonucleotide that is essential for hormone action and the transfer of information by the nervous system. (See Chapter 15.)

All Life from Life

- During the Renaissance (circa 1350–1700 A.D.), most people thought that some forms of life arose directly from inanimate or decaying matter by spontaneous generation.
  - For example, it was suggested that flies were produced from decaying meat.
- The Italian doctor and poet Francisco Redi attacked this idea.
- In 1668, Redi proposed that flies arose from other flies that laid eggs on the meat, not by spontaneous generation.
- He developed an experiment to test his hypothesis.
  - Redi set out several jars containing chunks of meat.
  - One jar contained meat exposed to both air and flies.
  - Another contained meat exposed to the air, but not to flies.
  - The third jar was sealed, so that its meat was not exposed to either air or flies.
  - Redi found maggots only in the first container.
  - The idea that a complex organism could come from a totally different substance was laid to rest.
- The invention of the microscope in the 1660s unveiled a vast new biological world teeming with tiny organisms such as bacteria.
- Some scientists believed that these organisms arose spontaneously from their rich chemical environment.
- Louis Pasteur completed experiments to disprove this idea. (See Figure 3.28 and Animated Tutorial 3.3.)
  - Pasteur boiled two containers of nutrient-rich medium to kill all microorganisms growing in both.
  - One container was open to air and dust particles; the other had a long "swan" neck that opened it to air but trapped dust particles bearing microorganisms.
  - Microbial growth was observed only in the container open to both the air and dust particle-bearing microorganisms.
  - Pasteur concluded that all life comes from existing life.
- Environmental and planetary conditions that exist on Earth today prevent life from arising from nonliving materials, as it might have during the Hadean.