BIOCHEMISTRY: LS2101

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Syllabus

Introductory biochemistry: biological interactions.

•Protein structure and folding, Enzymology, Enzyme kinetics, and allostery. vitamins and coenzymes.

•Overview of techniques in protein purification.

•Nucleic acid structure.

•Introduction to intermediary metabolism: Glycolysis, TCA cycle, Electron transport

Introductory biochemistry: biological interactions.

THE FOUNDATIONS OF BIOCHEMISTRY

Atom: is the smallest particle of an element that can exist either alone or in combination

Cell: is the smallest unit of a living body that can exist either alone or in combination

Living organisms are special:

A high degree of chemical complexity and microscopic organization.

Systems for extracting, transforming, and using energy from the environment

A capacity for precise self-replication and self-assembly

Mechanisms for sensing and responding to alterations in their surroundings

Defined functions for each of their components and regulated interactions among them

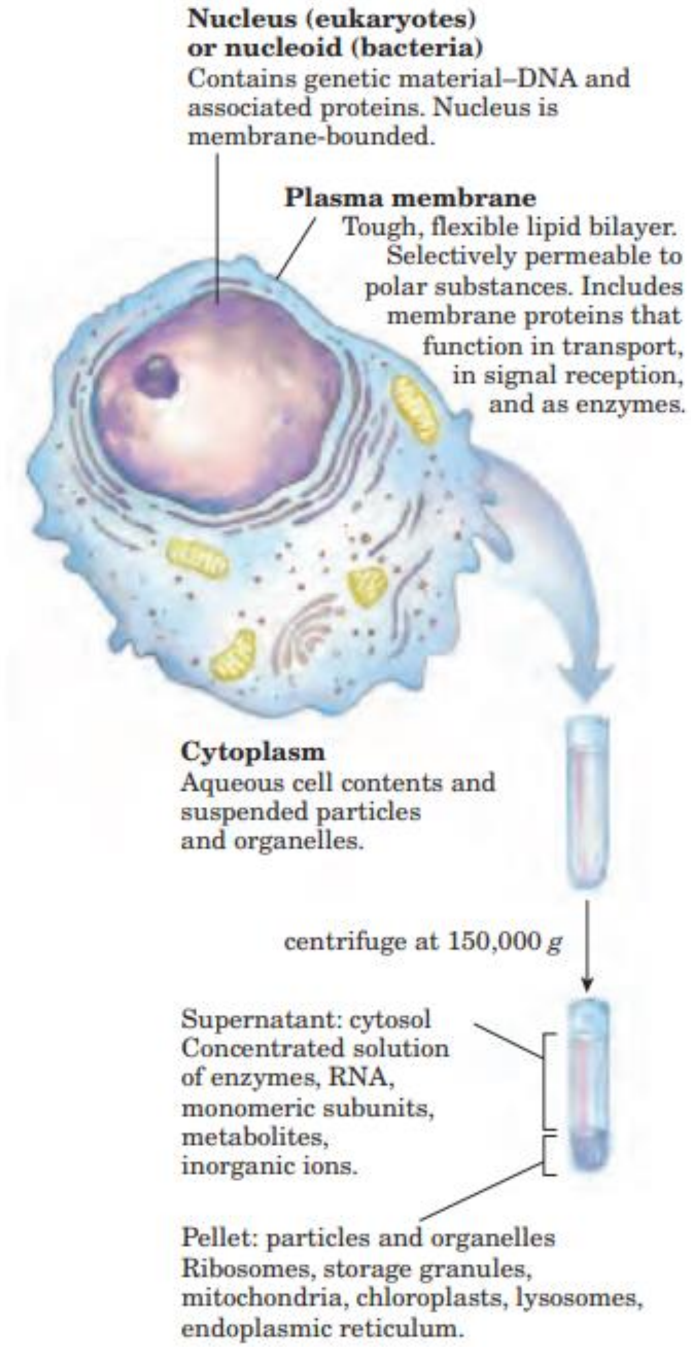
A history of evolutionary change

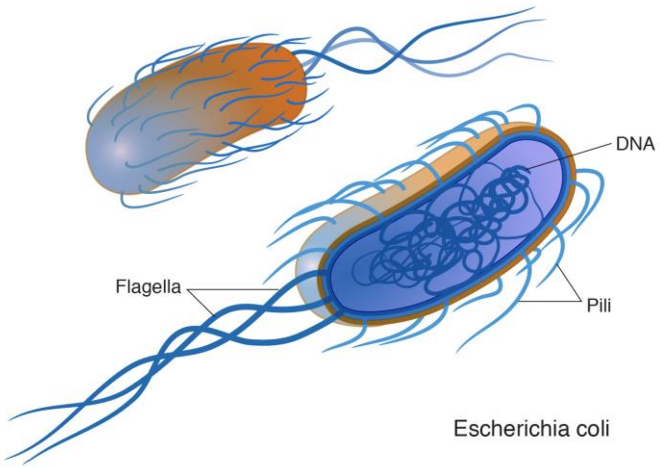
THE FOUNDATIONS OF BIOCHEMISTRY

1. Cellular Foundations
2. Chemical Foundations
3. Physical Foundations
4. Genetic Foundations
5. Evolutionary Foundations

1. Cellular Foundations

Cells Are the Structural and Functional Units of All Living Organisms





1. Cellular Foundations

Cellular Dimensions Are Limited by Oxygen Diffusion

Ratio of cells Surface Area to Volume

Animal and plant cells are generally between 5 to 100 micro meter in diameter

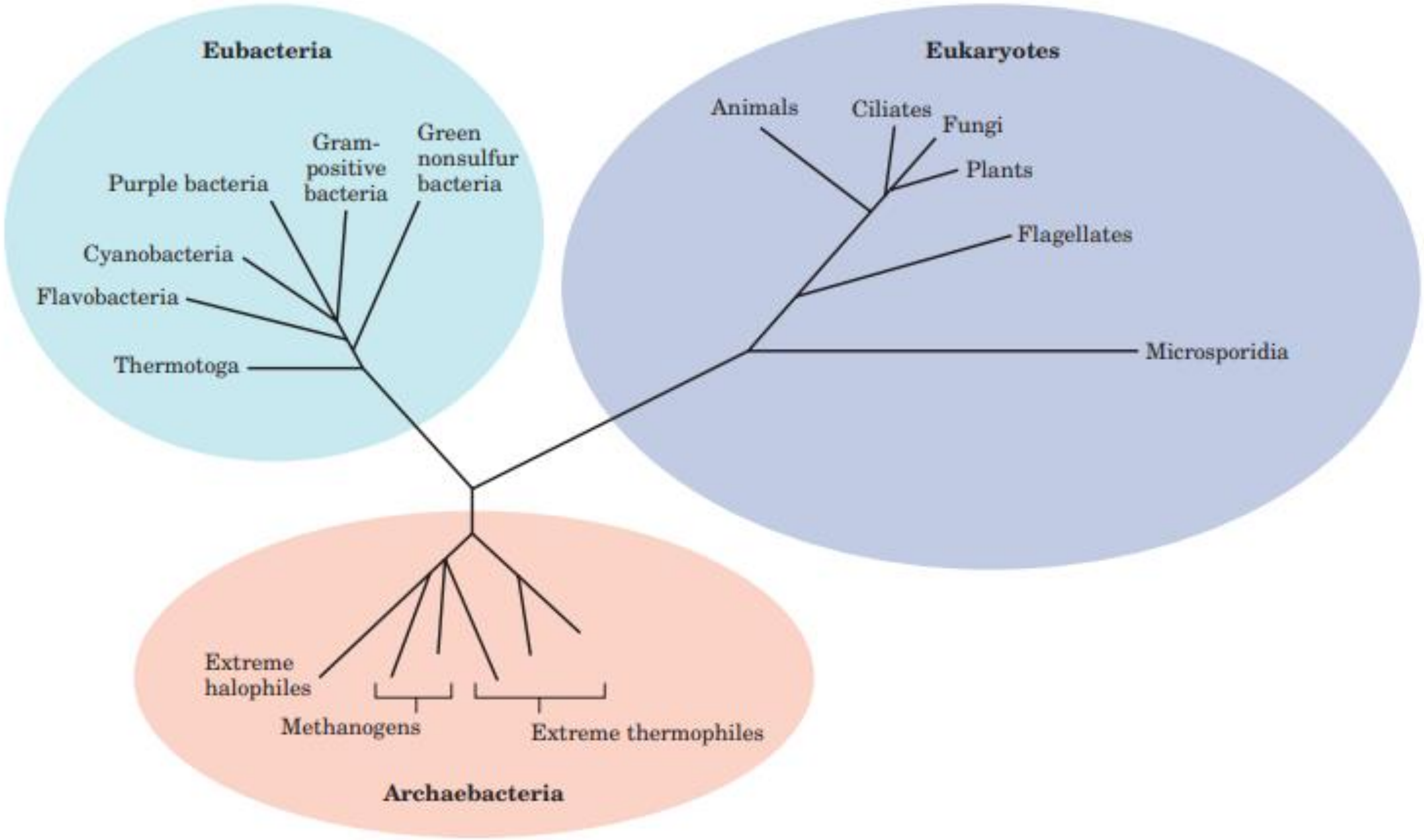
Bacteria are generally 1 to 5 micro meter in length

Mycoplasma: 300 nm

Ribosome: 20 nm

1. Cellular Foundations

There Are Three Distinct Domains of Life



1. Cellular Foundations

Organisms can be classified according to their source of energy

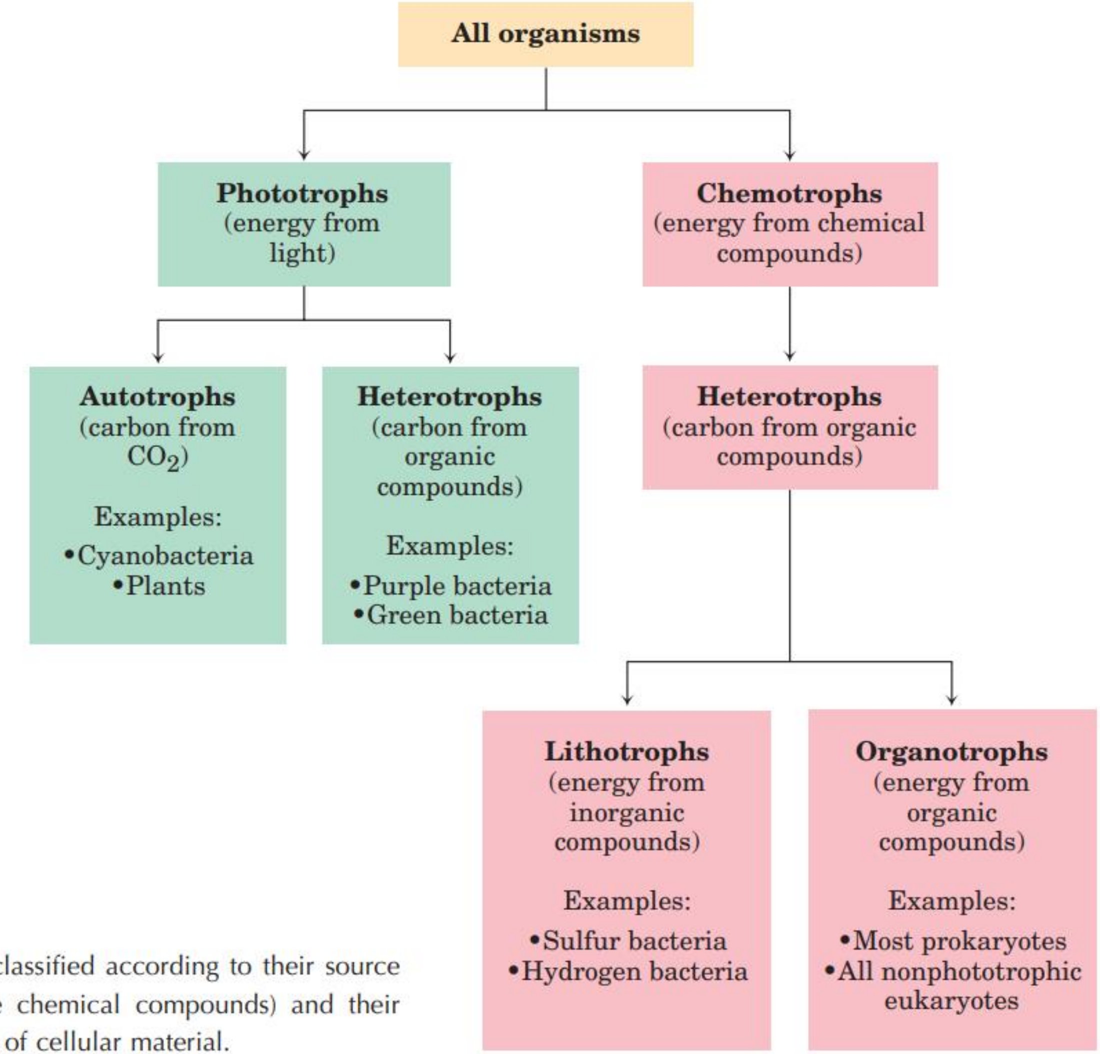
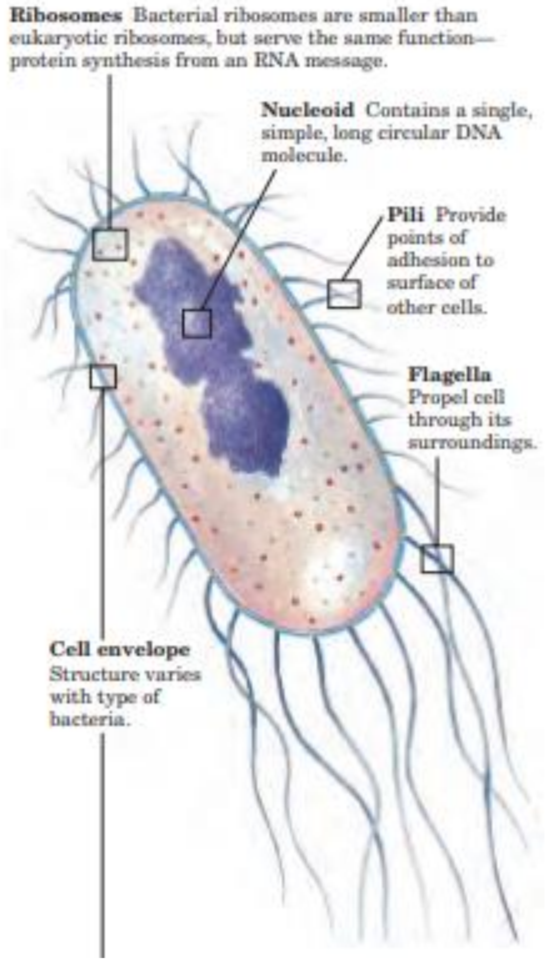
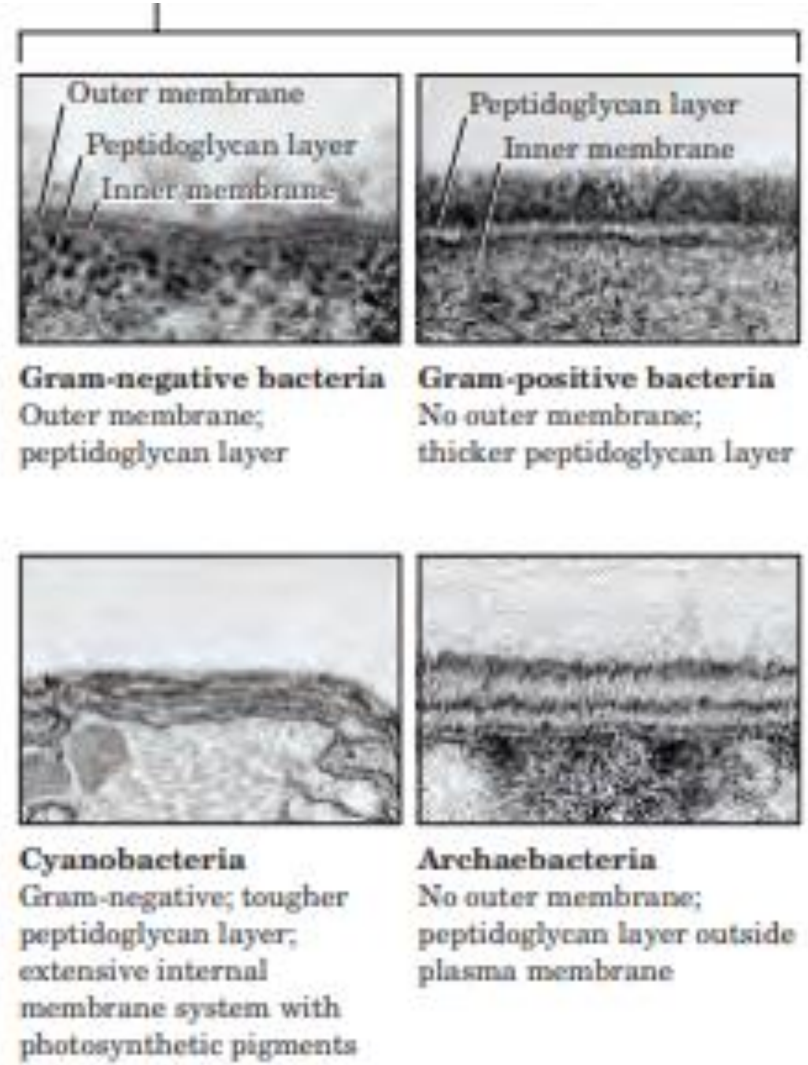


FIGURE 1–5 Organisms can be classified according to their source of energy (sunlight or oxidizable chemical compounds) and their source of carbon for the synthesis of cellular material.

1. Cellular Foundations

Escherichia coli Is the Most-Studied Prokaryotic Cell





Eukaryotic Cells Have a Variety of Membranous Organelles, Which Can Be Isolated for Study

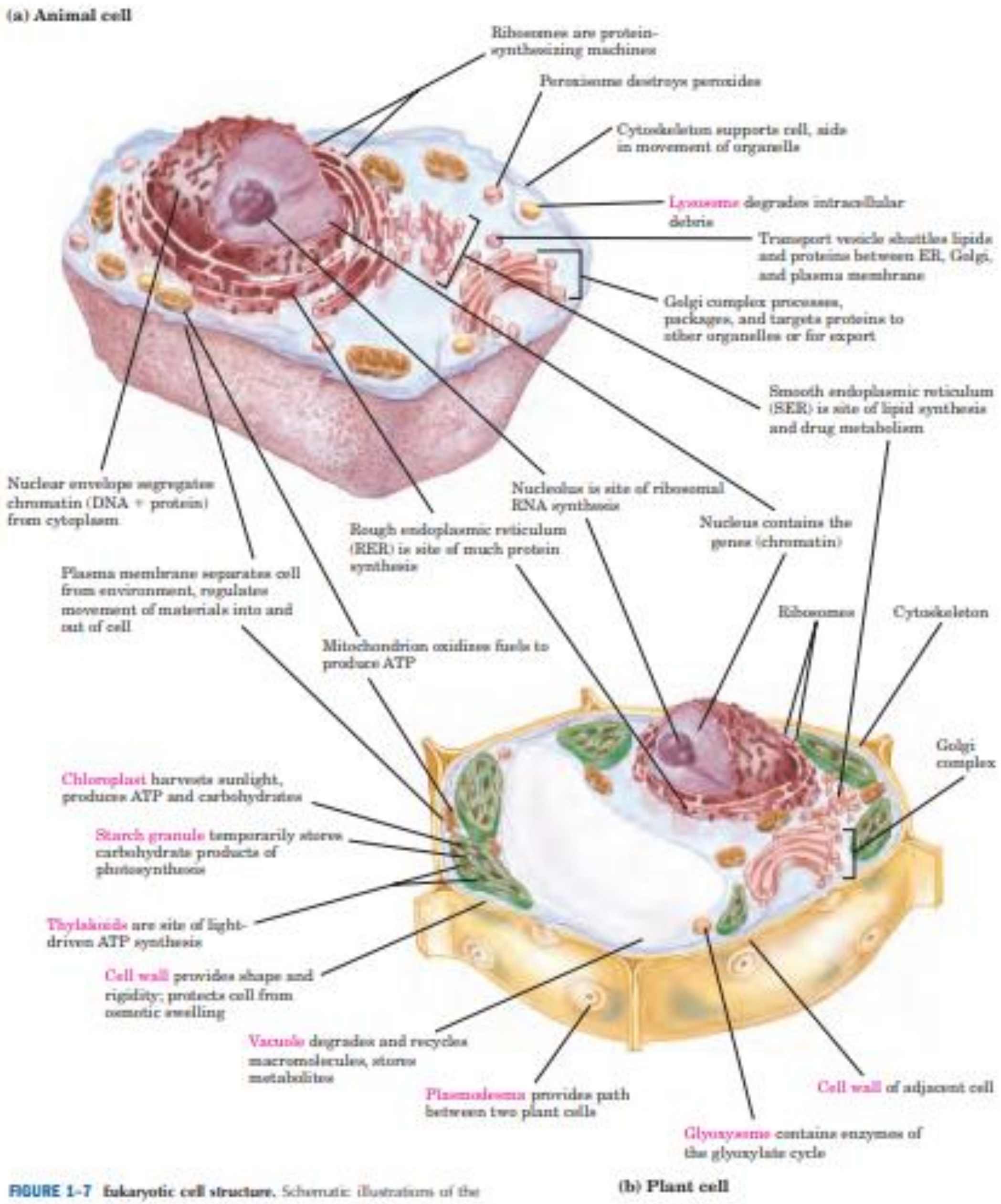


FIGURE 1–7 Eukaryotic cell structure. Schematic illustrations of the two major types of eukaryotic cell: (a) a representative animal cell

1. Cellular Foundations

Subcellular fractionation of tissue

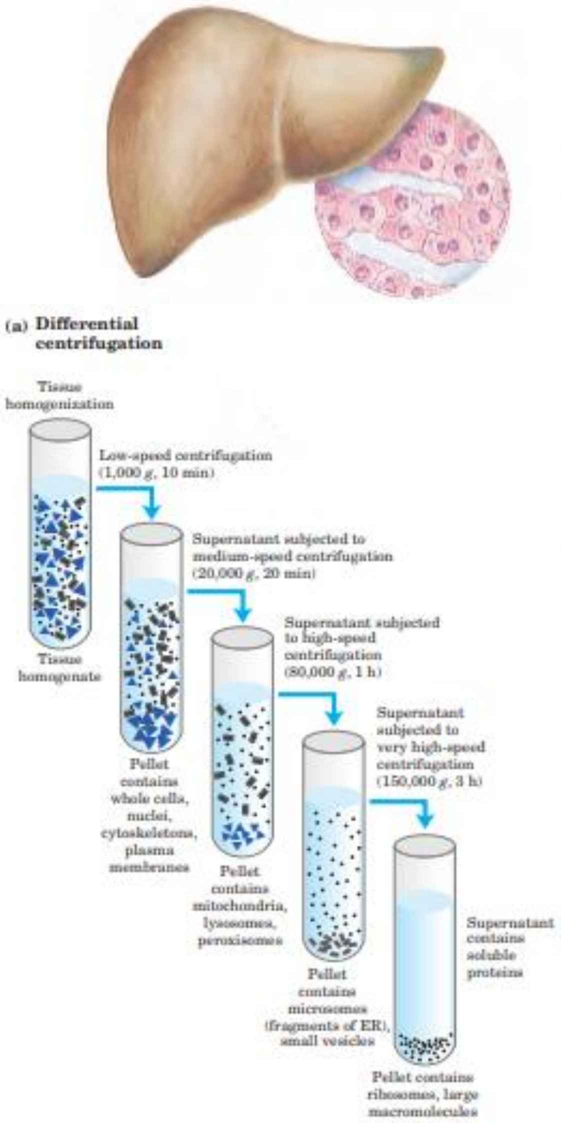
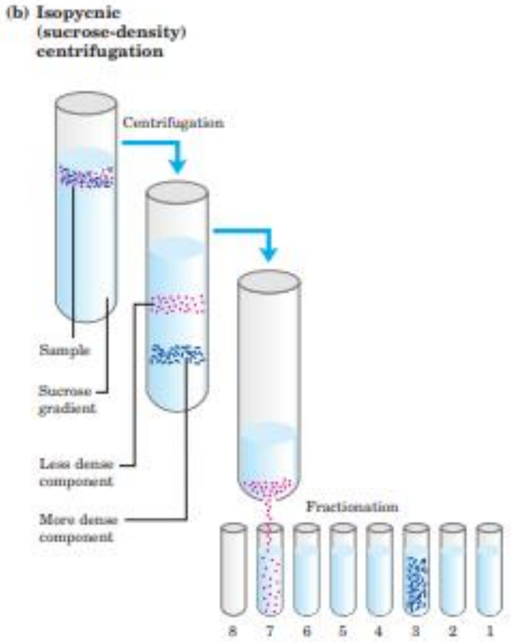
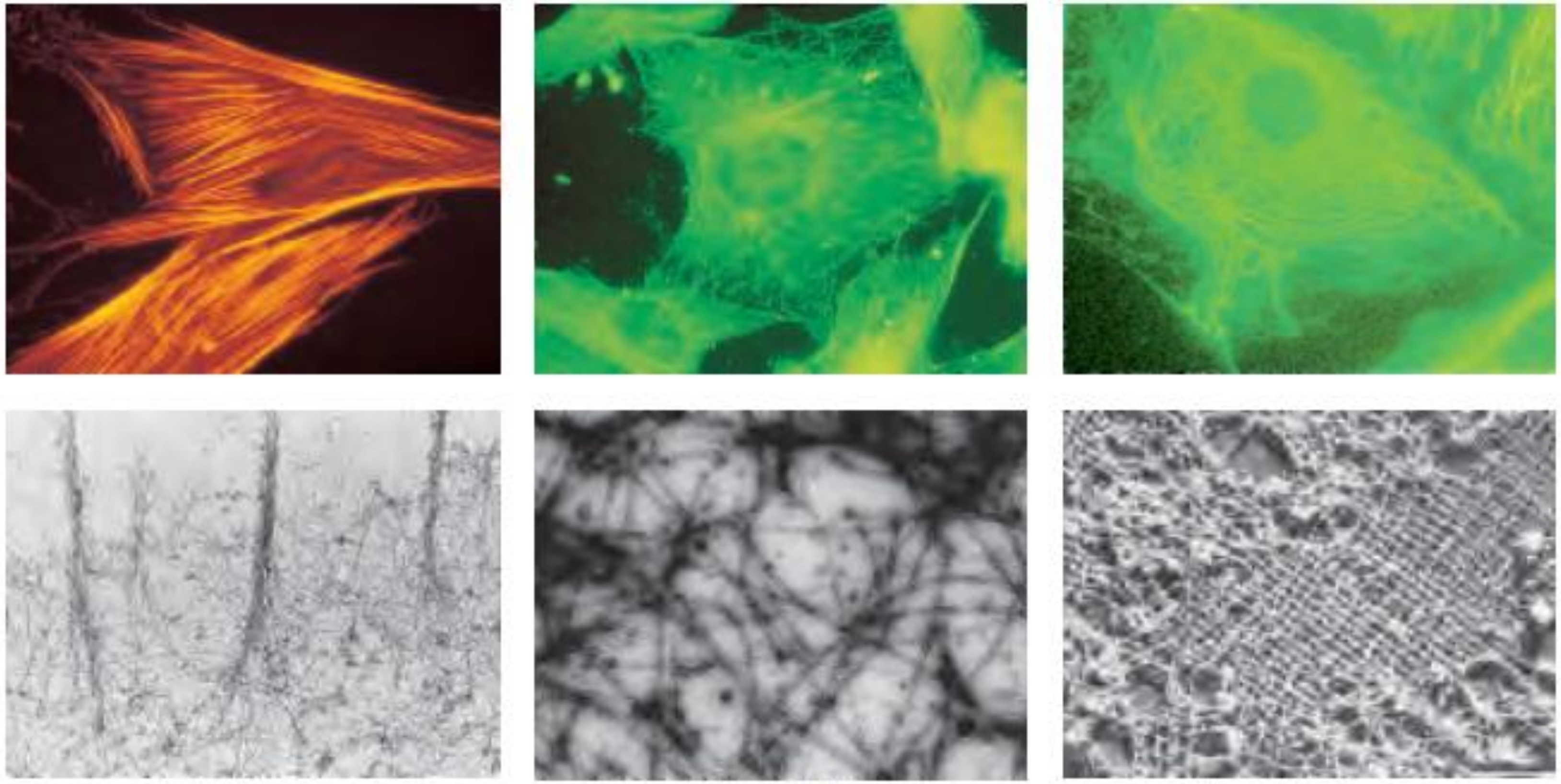


FIGURE 1–8 Subcellular fractionation of tissue. A tissue such as liver is first mechanically homogenized to break cells and disperse their contents in an aqueous buffer. The sucrose medium has an osmotic pressure similar to that in organelles, thus preventing diffusion of water into the organelles, which would swell and burst. **(a)** The large and small particles in the suspension can be separated by centrifugation at different speeds, or **(b)** particles of different density can be separated by isopycnic centrifugation. In isopycnic centrifugation, a centrifuge tube is filled with a solution, the density of which increases from top to bottom; a solute such as sucrose is dissolved at different concentrations to produce the density gradient. When a mixture of organelles is layered on top of the density gradient and the tube is centrifuged at high speed, individual organelles sediment until their buoyant density exactly matches that in the gradient. Each layer can be collected separately.



1. Cellular Foundations

The Cytoplasm Is Organized by the Cytoskeleton and Is Highly Dynamic



Actin stress fibers
(a)

Microtubules
(b)

Intermediate filaments
(c)

FIGURE 1-9 The three types of cytoskeletal filaments. The upper panels show epithelial cells photographed after treatment with antibodies that bind to and specifically stain **(a)** actin filaments bundled together to form "stress fibers," **(b)** microtubules radiating from the cell center, and **(c)** intermediate filaments extending throughout the cytoplasm. For these experiments, antibodies that specifically recognize actin, tubulin, or intermediate filament proteins are covalently attached to a fluorescent compound. When the cell is viewed with a fluorescence microscope, only the stained structures are visible. The lower panels show each type of filament as visualized by **(a, b)** transmission or **(c)** scanning electron microscopy.

1. Cellular Foundations

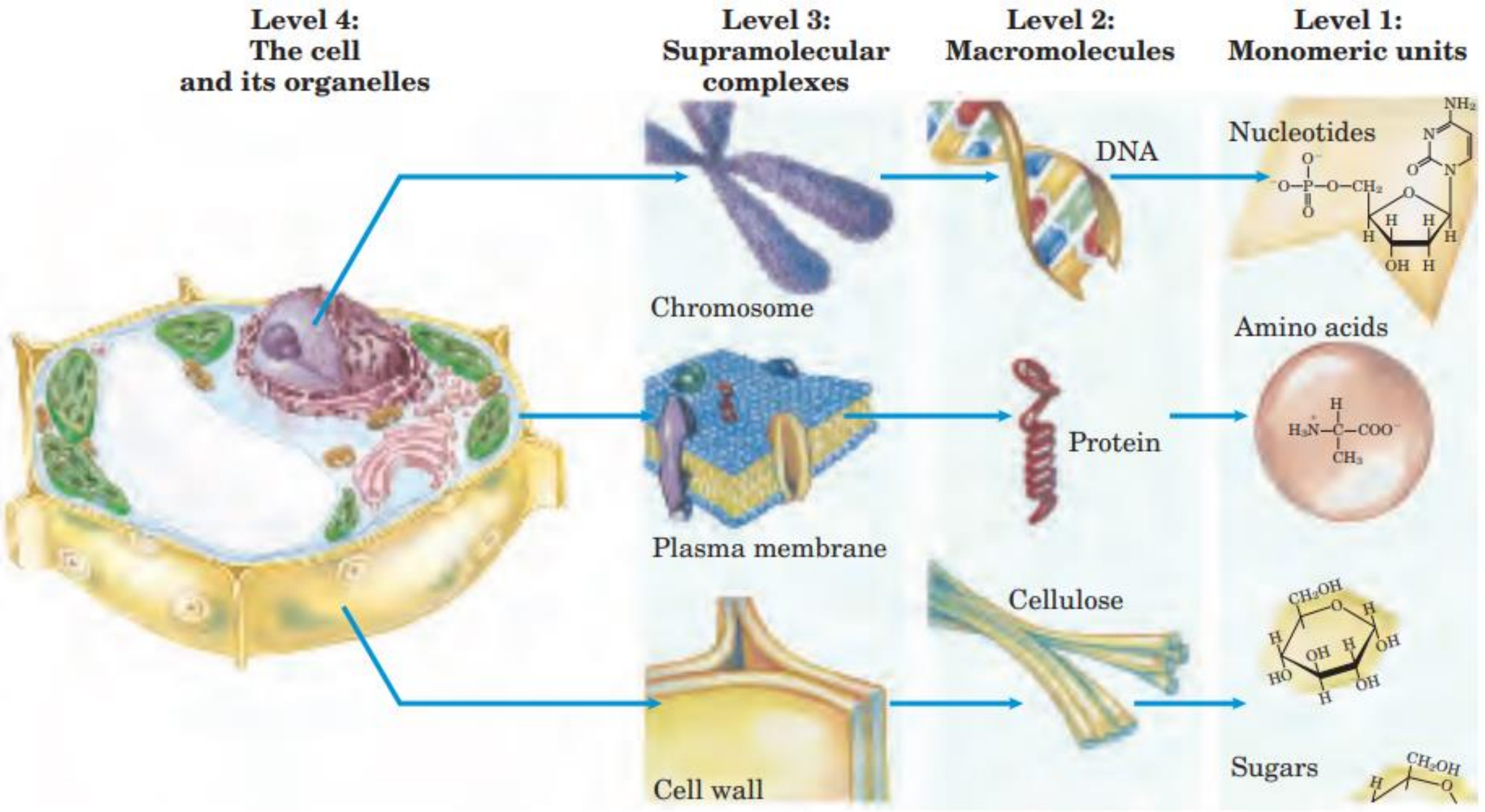


FIGURE 1–11 Structural hierarchy in the molecular organization of cells. In this plant cell, the nucleus is an organelle containing several types of supramolecular complexes, including chromosomes. Chromosomes consist of macromolecules of DNA and many different proteins. Each type of macromolecule is made up of simple subunits—DNA of nucleotides (deoxyribonucleotides), for example.

THE FOUNDATIONS OF BIOCHEMISTRY

1. Cellular Foundations

2. Chemical Foundations

3. Physical Foundations

4. Genetic Foundations

5. Evolutionary Foundations

2. Chemical Foundations

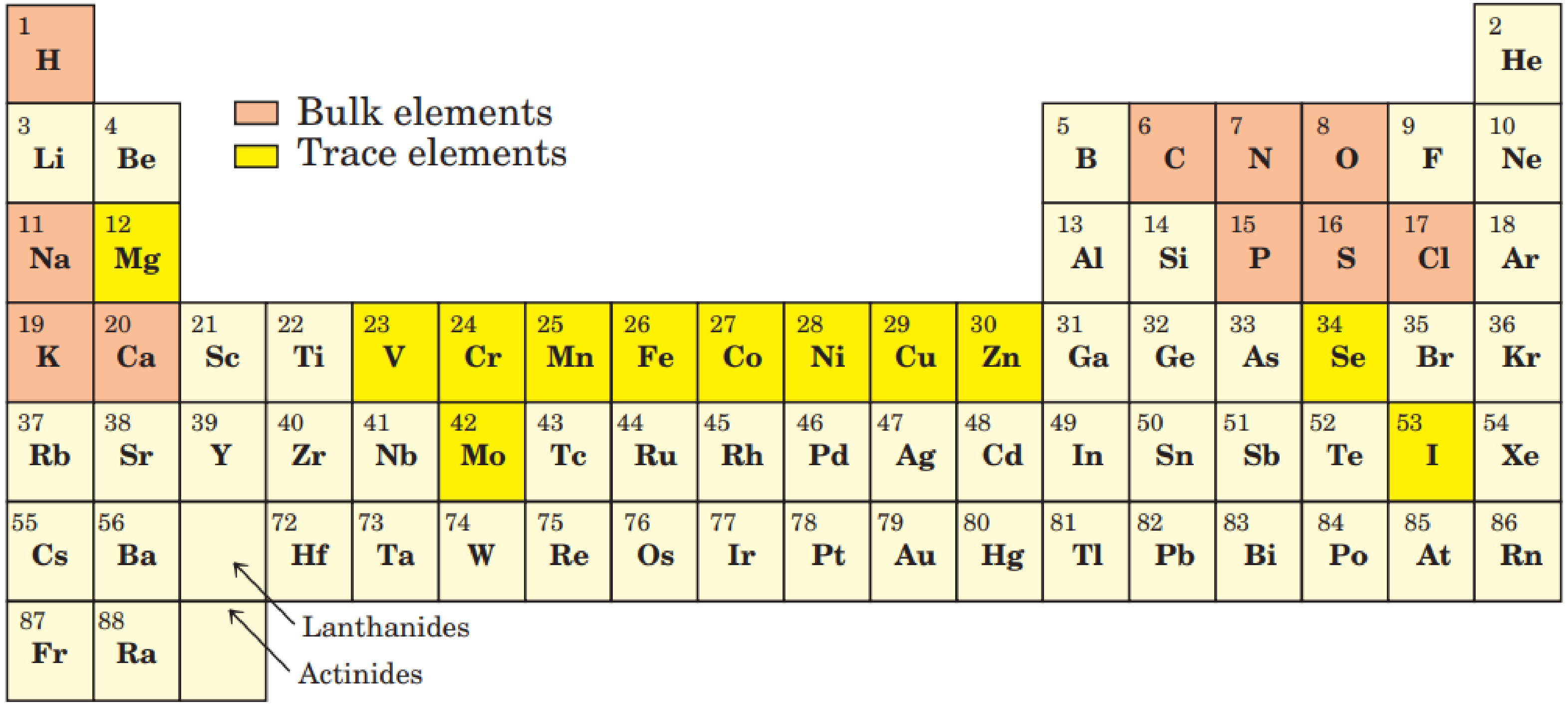
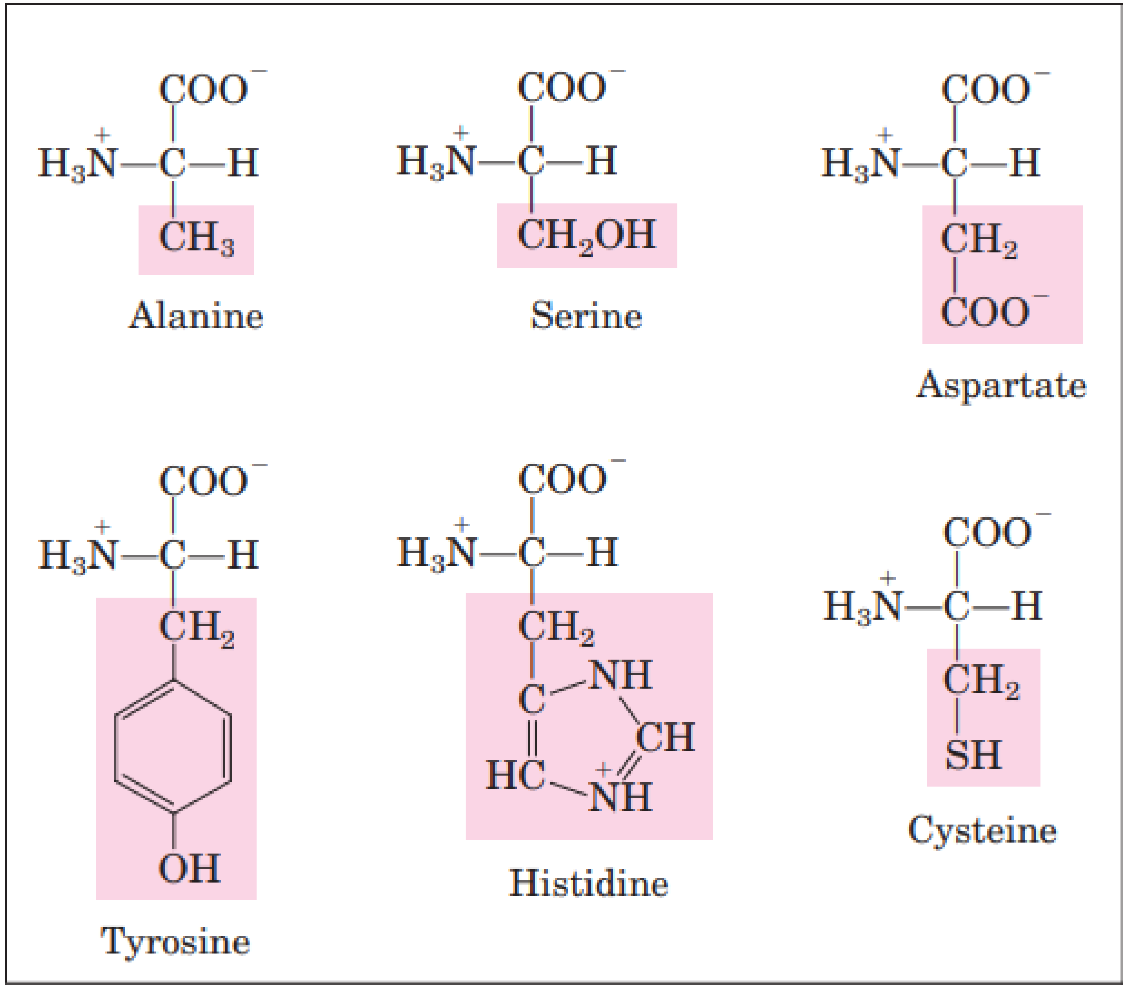


FIGURE 1–12 Elements essential to animal life and health. Bulk elements (shaded orange) are structural components of cells and tissues and are required in the diet in gram quantities daily. For trace elements (shaded bright yellow), the requirements are much smaller: for humans, a few milligrams per day of Fe, Cu, and Zn, even less of the others. The elemental requirements for plants and microorganisms are similar to those shown here; the ways in which they acquire these elements vary.

2. Chemical Foundations

Cells Build Supramolecular Structures from smaller components of organic molecules

(a) Some of the amino acids of proteins



2. Chemical Foundations

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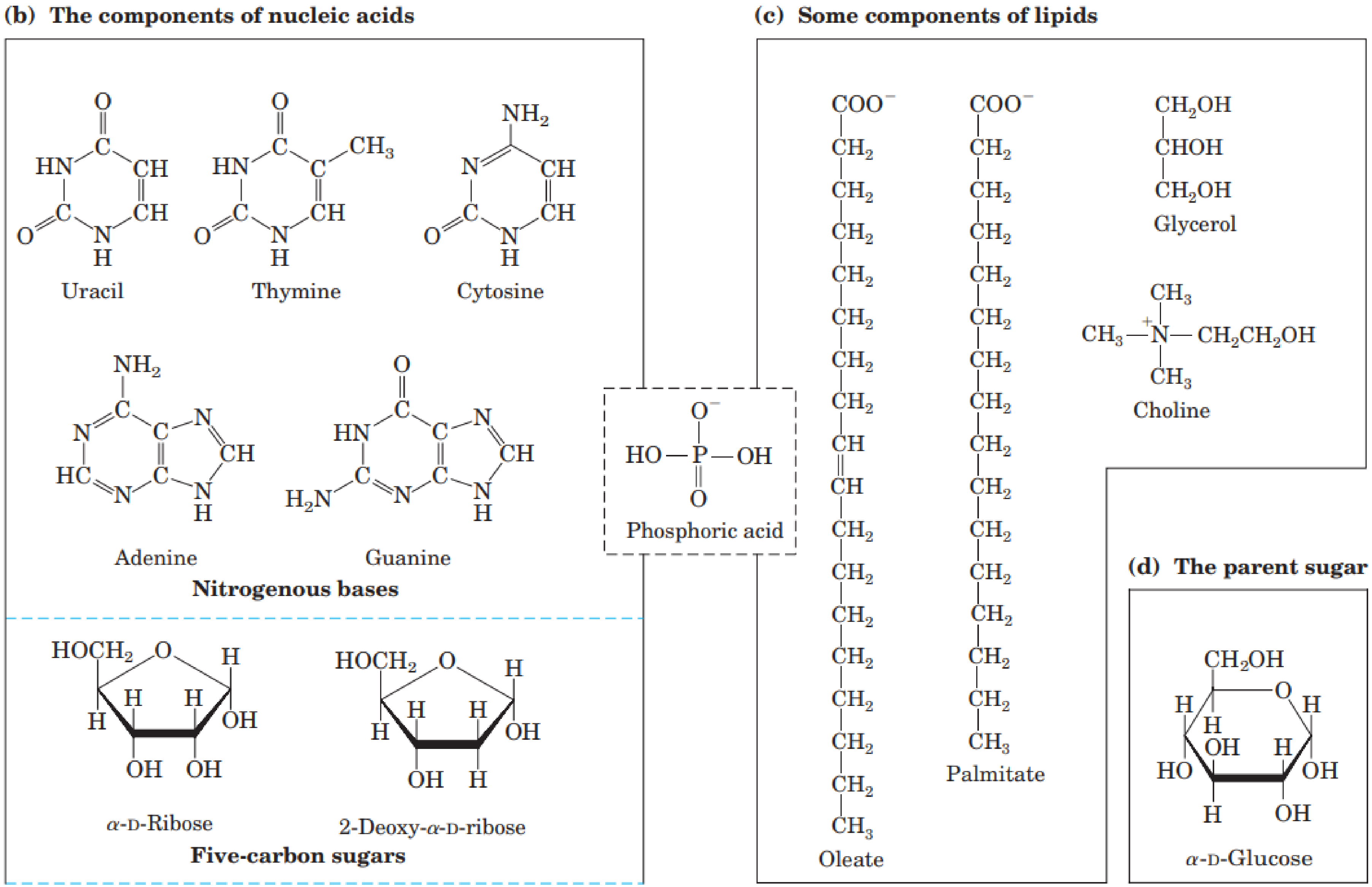

2. Chemical Foundations

TABLE 1–1 Strengths of Bonds Common in Biomolecules

Type of bond	*Bond dissociation energy* (kJ/mol)*	*Type of bond*	*Bond dissociation energy (kJ/mol)*
Single bonds		**Double bonds**	
O—H	470	C=O	712
H—H	435	C=N	615
P—O	419	C=C	611
C—H	414	P=O	502
N—H	389		
C—O	352	**Triple bonds**	
C—C	348	C≡C	816
S—H	339	N≡N	930
C—N	293		
C—S	260		
N—O	222		
S—S	214		

*The greater the energy required for bond dissociation (breakage), the stronger the bond.

2. Chemical Foundations

Carbon: is special and the
central element to life

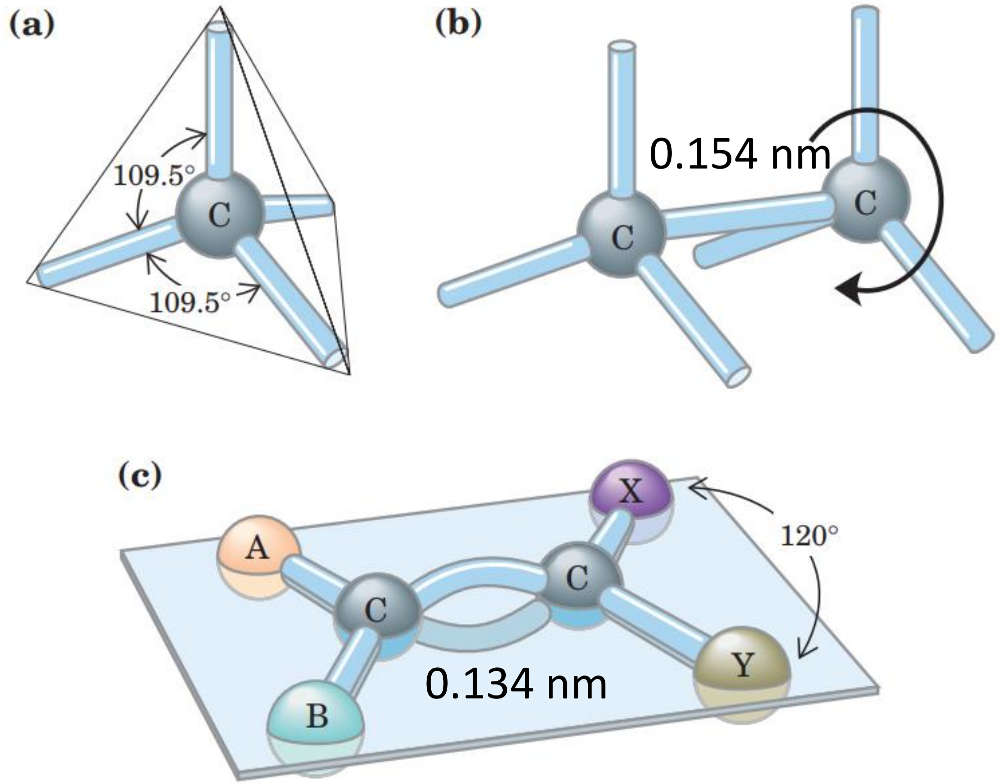

FIGURE 1–14 Geometry of carbon bonding. (a) Carbon atoms have a characteristic tetrahedral arrangement of their four single bonds. **(b)** Carbon–carbon single bonds have freedom of rotation, as shown for the compound ethane (CH_3—CH_3). **(c)** Double bonds are shorter and do not allow free rotation. The two doubly bonded carbons and the atoms designated A, B, X, and Y all lie in the same rigid plane.

2. Chemical Foundations

TABLE 1–1 Strengths of Bonds Common in Biomolecules

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H—H	435	C═N	615
P—O	419	$\boxed{\text{C═C} \quad 611}$	
C—H	414	P═O	502
N—H	389		
C—O	352	**Triple bonds**	
$\boxed{\text{C—C} \quad 348}$		$\boxed{\text{C≡C} \quad 816}$	
S—H	339	N≡N	930
C—N	293		
C—S	260		
N—O	222		
S—S	214		

*The greater the energy required for bond dissociation (breakage), the stronger the bond.

0.154 nm

0.134 nm

2. Chemical Foundations

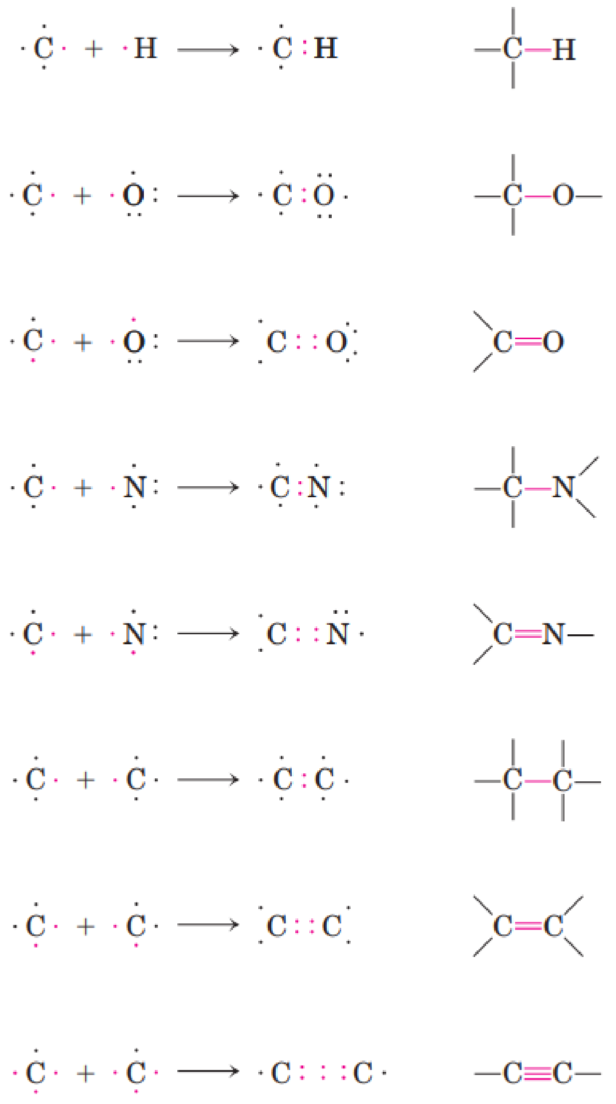

FIGURE 1–13 Versatility of carbon bonding. Carbon can form covalent single, double, and triple bonds (in red), particularly with other carbon atoms. Triple bonds are rare in biomolecules.

2. Chemical Foundations

R is an abbreviation for radical

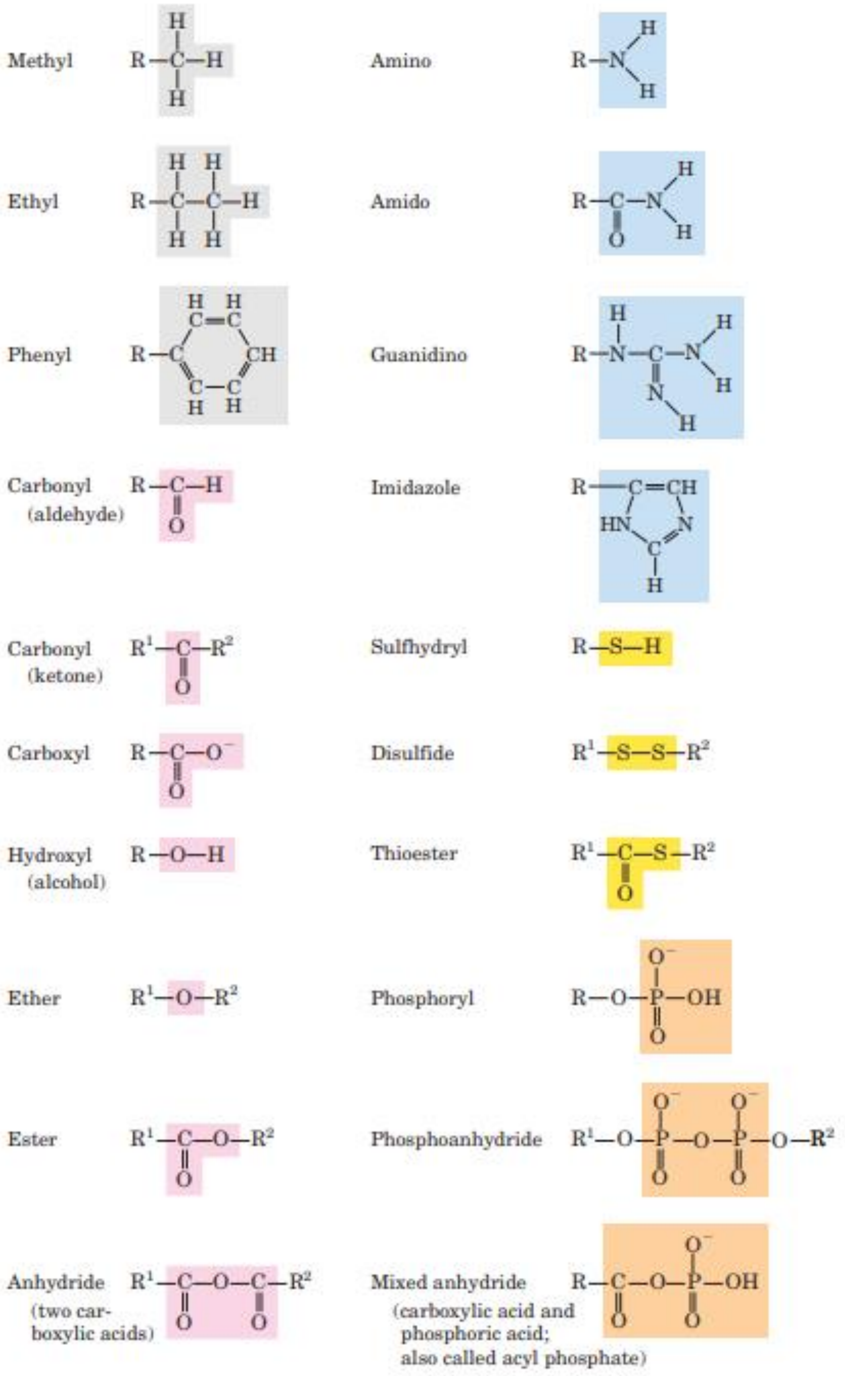

FIGURE 1-15 Some common functional groups of biomolecules. In this figure and throughout the book, we use R to represent "any substituent." It may be as simple as a hydrogen atom, but typically it is a carbon-containing moiety. When two or more substituents are shown in a molecule, we designate them R^1, R^2, and so forth.

TABLE 1-1 Strengths of Bonds Common in Biomolecules

Type of bond	*Bond dissociation energy* (kJ/mol)*	*Type of bond*	*Bond dissociation energy (kJ/mol)*
Single bonds		**Double bonds**	
O—H	470	C=O	712
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S—S	214		

*The greater the energy required for bond dissociation (breakage), the stronger the bond.

2. Chemical Foundations

Cells Contain a Universal Set of Small Molecules: Amino acids, ATP, GTP etc

Secondary metabolites: Caffeine, Nicotine, Quinine etc

Metabolome: The entire collection of small molecules in a given cell has been called that cell's metabolome

2. Chemical Foundations

Macromolecules Are the Major Constituents of Cells

DNA

RNA

Protein

Lipid

Carbohydrates

2. Chemical Foundations

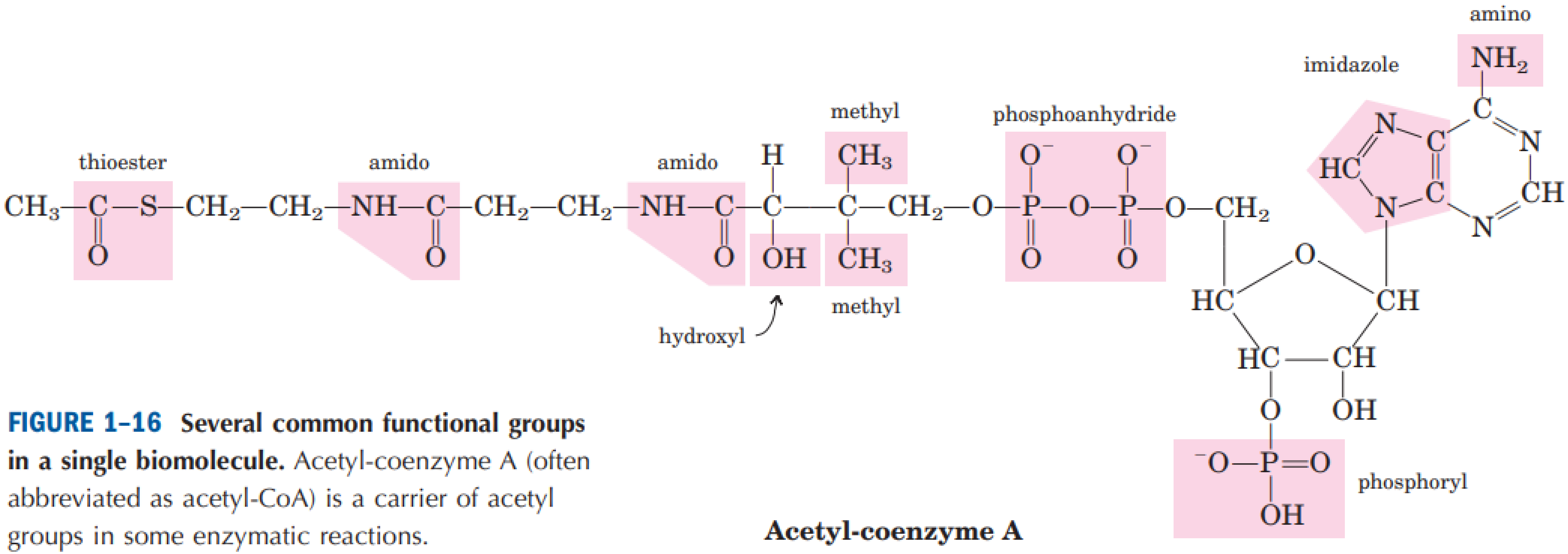


FIGURE 1–16 Several common functional groups in a single biomolecule. Acetyl-coenzyme A (often abbreviated as acetyl-CoA) is a carrier of acetyl groups in some enzymatic reactions.

2. Chemical Foundations

TABLE 1–2 Molecular Components of an *E. coli* Cell

	Percentage of total weight of cell	*Approximate number of different molecular species*
Water	70	1
Proteins	15	3,000
Nucleic acids		
DNA	1	1
RNA	6	>3,000
Polysaccharides	3	5
Lipids	2	20
Monomeric subunits and intermediates	2	500
Inorganic ions	1	20

2. Chemical Foundations

Three-Dimensional Structure Is Described by Configuration and Conformation

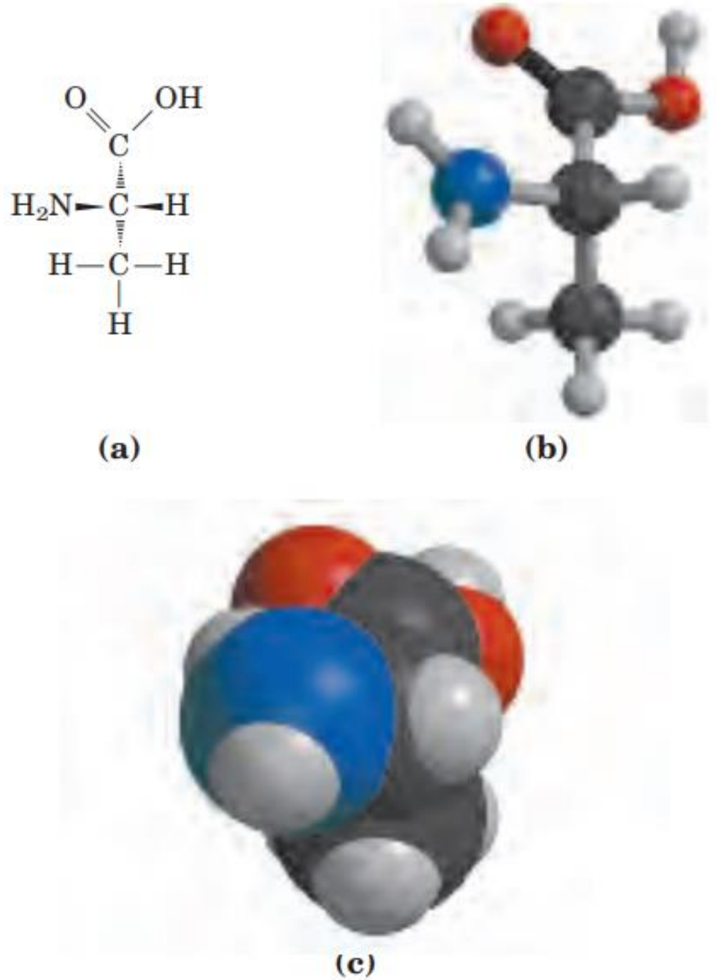


FIGURE 1–17 Representations of molecules. Three ways to represent the structure of the amino acid alanine. **(a)** Structural formula in perspective form: a solid wedge (━) represents a bond in which the atom at the wide end projects out of the plane of the paper, toward the reader; a dashed wedge (┅) represents a bond extending behind the plane of the paper. **(b)** Ball-and-stick model, showing relative bond lengths and the bond angles. **(c)** Space-filling model, in which each atom is shown with its correct relative van der Waals radius.

2. Chemical Foundations

Configuration

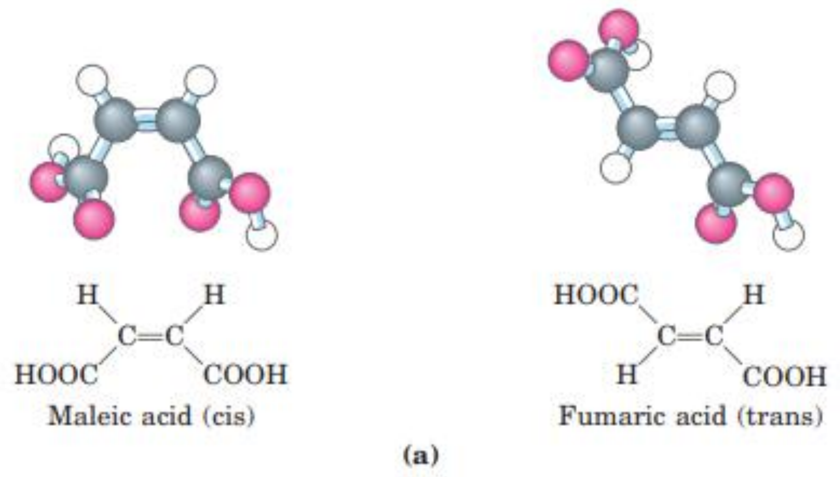
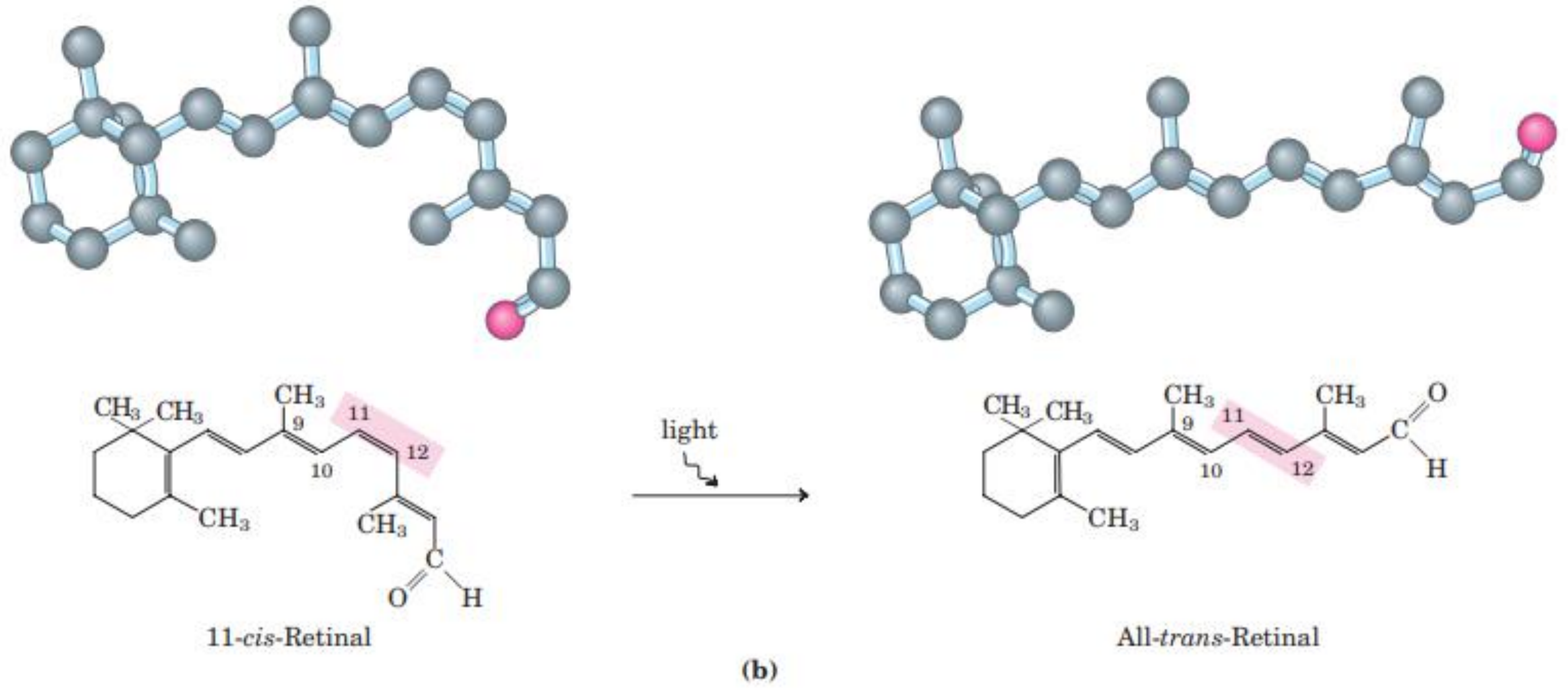


FIGURE 1–18 Configurations of geometric isomers. **(a)** Isomers such as maleic acid and fumaric acid cannot be interconverted without breaking covalent bonds, which requires the input of much energy. **(b)** In the vertebrate retina, the initial event in light detection is the absorption of visible light by 11-*cis*-retinal. The energy of the absorbed light (about 250 kJ/mol) converts 11-*cis*-retinal to all-*trans*-retinal, triggering electrical changes in the retinal cell that lead to a nerve impulse. (Note that the hydrogen atoms are omitted from the ball-and-stick models for the retinals.)



2. Chemical Foundations

Stereoisomers

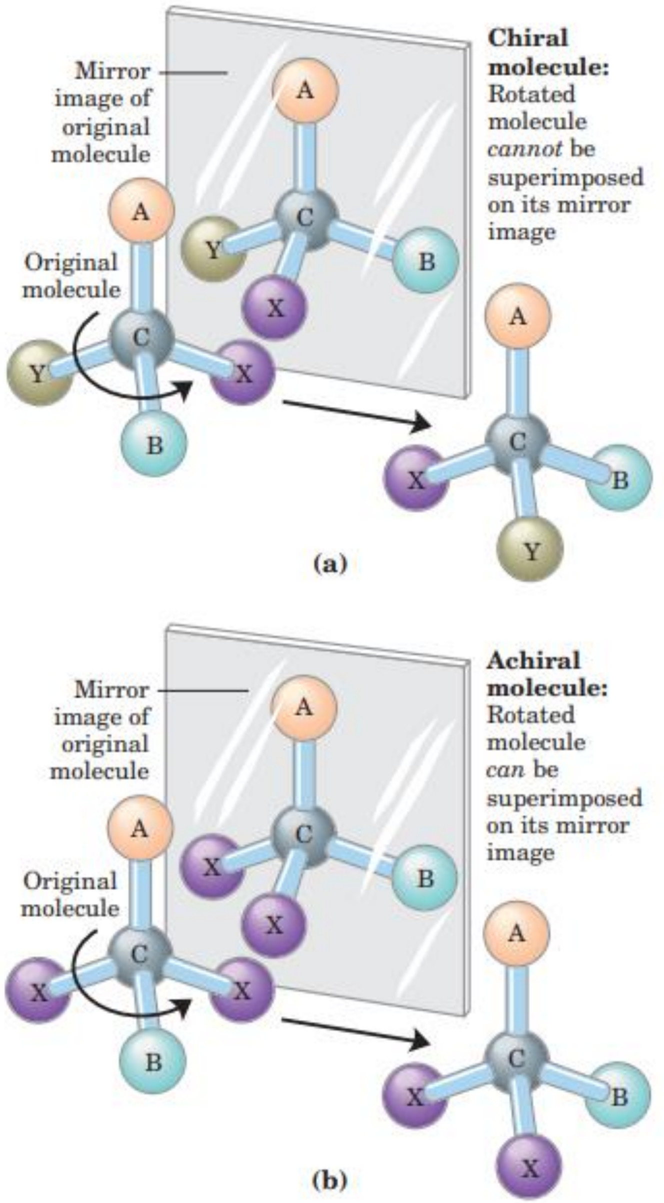
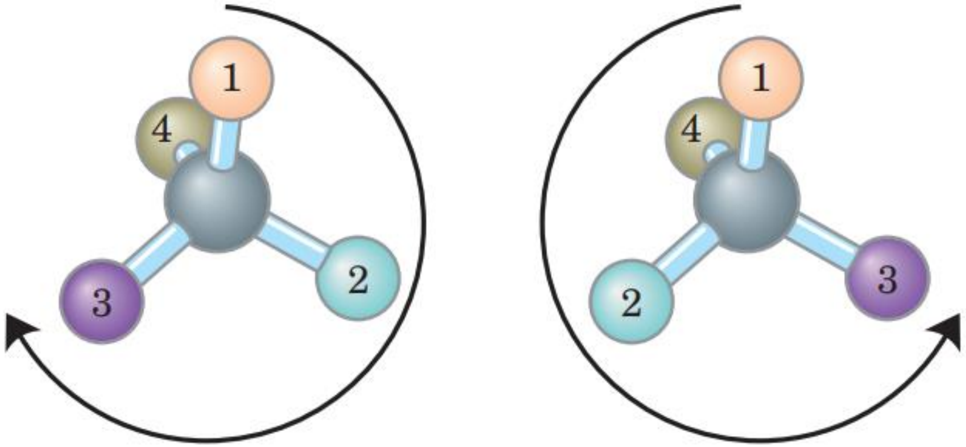


FIGURE 1–19 Molecular asymmetry: chiral and achiral molecules. **(a)** When a carbon atom has four different substituent groups (A, B, X, Y), they can be arranged in two ways that represent nonsuperimposable mirror images of each other (enantiomers). This asymmetric carbon atom is called a chiral atom or chiral center. **(b)** When a tetrahedral carbon has only three dissimilar groups (i.e., the same group occurs twice), only one configuration is possible and the molecule is symmetric, or achiral. In this case the molecule is superimposable on its mirror image: the molecule on the left can be rotated counterclockwise (when looking down the vertical bond from A to C) to create the molecule in the mirror.

2. Chemical Foundations

Optical Activity



Clockwise
(R)

Counterclockwise
(S)

2. Chemical Foundations

Optical Activity

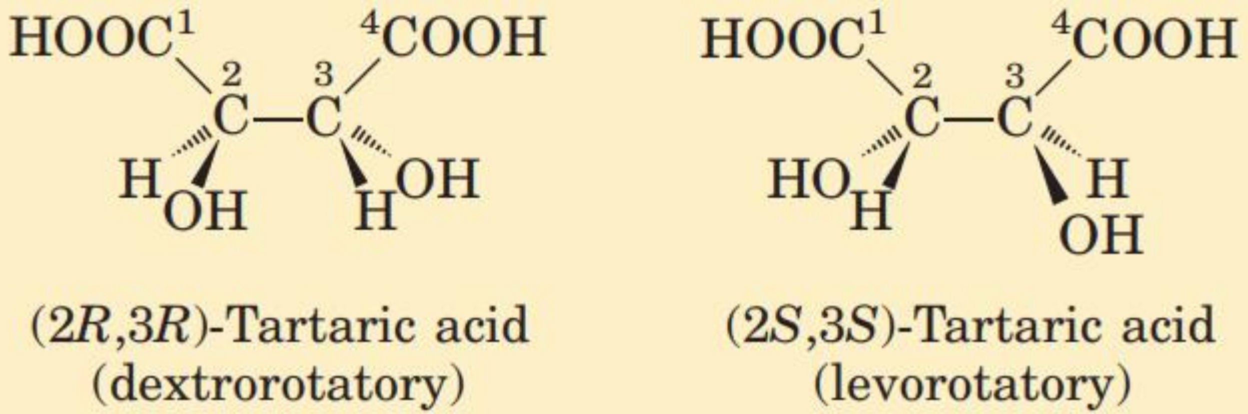


FIGURE 1 Pasteur separated crystals of two stereoisomers of tartaric acid and showed that solutions of the separated forms rotated polarized light to the same extent but in opposite directions. These dextrorotatory and levorotatory forms were later shown to be the (*R*,*R*) and (*S*,*S*) isomers represented here. The RS system of nomenclature is explained in the text.

2. Chemical Foundations

Conformations

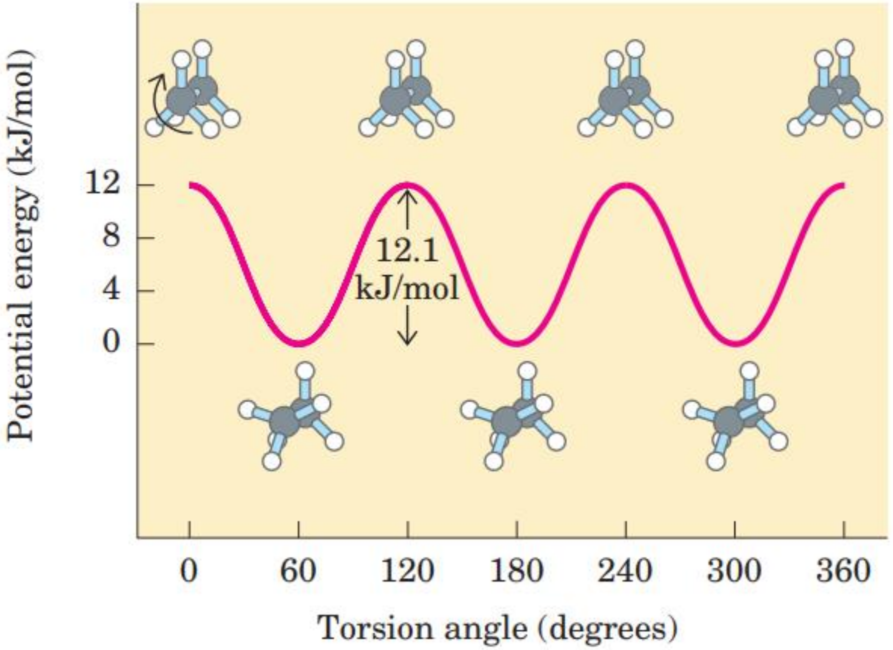


FIGURE 1–21 Conformations. Many conformations of ethane are possible because of freedom of rotation around the C—C bond. In the ball-and-stick model, when the front carbon atom (as viewed by the reader) with its three attached hydrogens is rotated relative to the rear carbon atom, the potential energy of the molecule rises to a maximum in the fully eclipsed conformation (torsion angle 0°, 120°, etc.), then falls to a minimum in the fully staggered conformation (torsion angle 60°, 180°, etc.). Because the energy differences are small enough to allow rapid interconversion of the two forms (millions of times per second), the eclipsed and staggered forms cannot be separately isolated.

2. Chemical Foundations

Interactions between Biomolecules Are Stereospecific

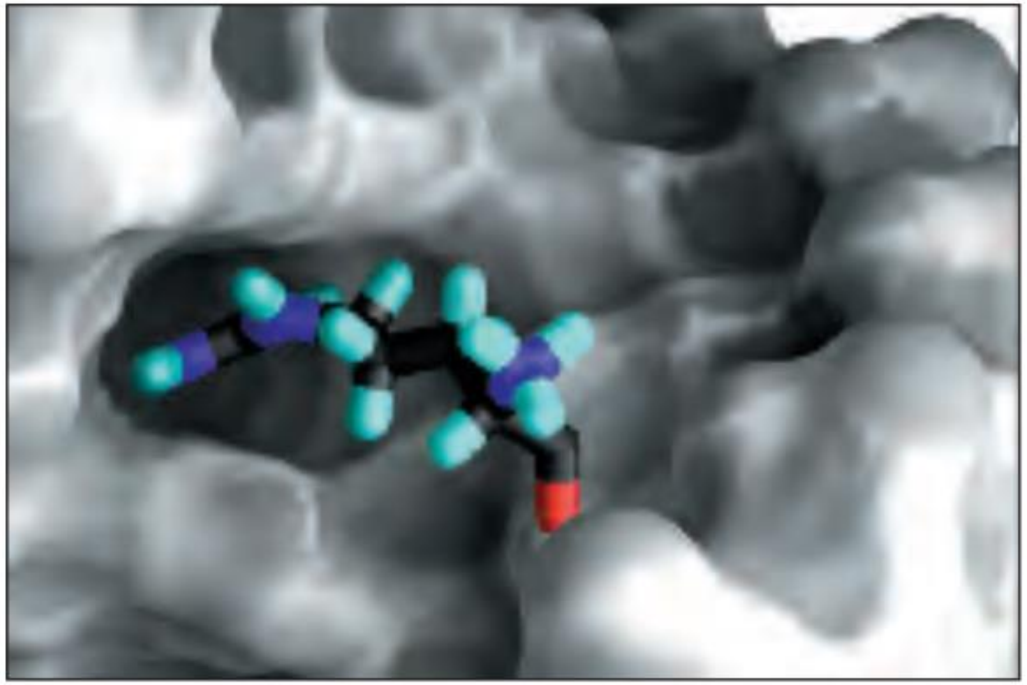
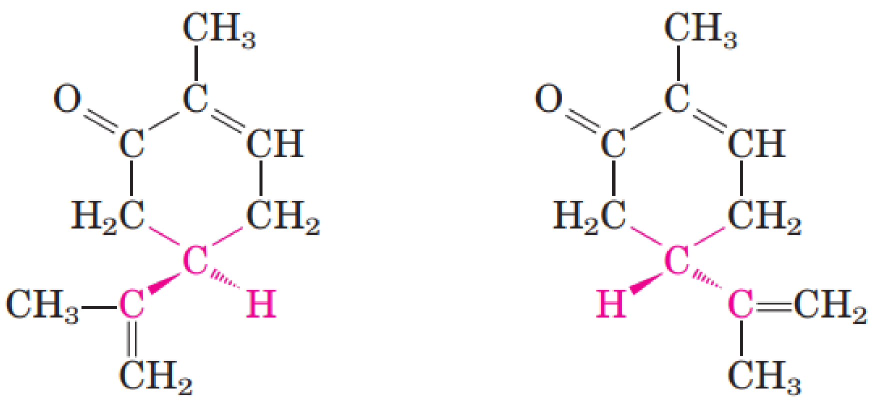


FIGURE 1–22 Complementary fit between a macromolecule and a small molecule. A segment of RNA from the regulatory region TAR of the human immunodeficiency virus genome (gray) with a bound argininamide molecule (colored), representing one residue of a protein that binds to this region. The argininamide fits into a pocket on the RNA surface and is held in this orientation by several noncovalent interactions with the RNA. This representation of the RNA molecule is produced with the computer program GRASP, which can calculate the shape of the outer surface of a macromolecule, defined either by the van der Waals radii of all the atoms in the molecule or by the "solvent exclusion volume," into which a water molecule cannot penetrate.

2. Chemical Foundations

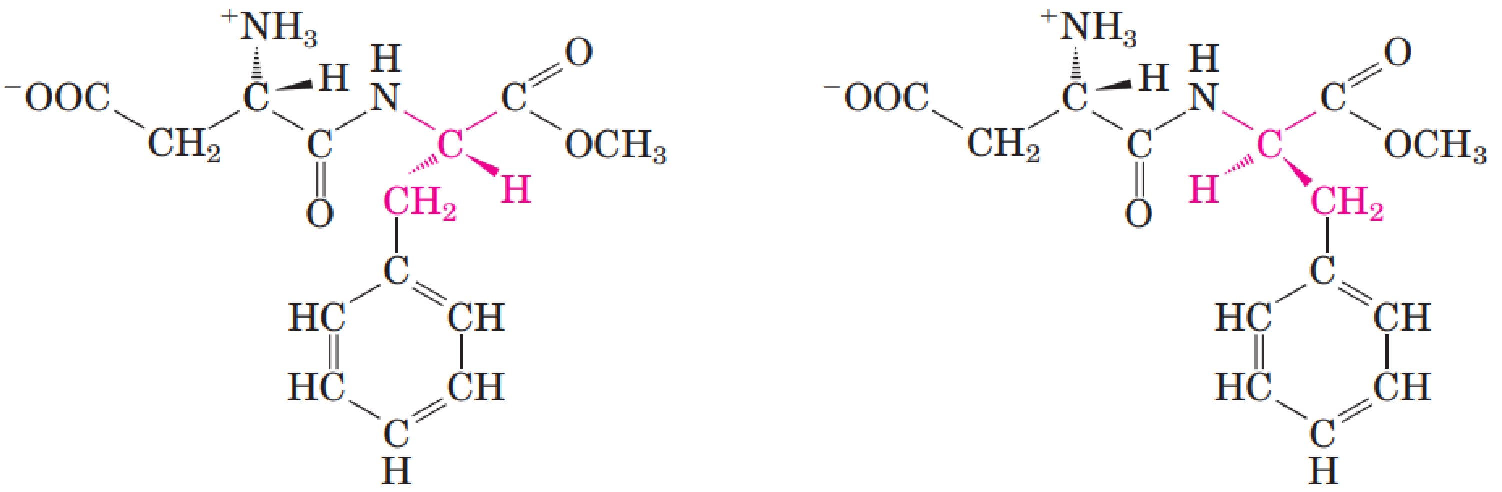
FIGURE 1–23 Stereoisomers distinguishable by smell and taste in humans. (a) Two stereoisomers of carvone: (*R*)-carvone (isolated from spearmint oil) has the characteristic fragrance of spearmint; (*S*)-carvone (from caraway seed oil) smells like caraway. **(b)** Aspartame, the artificial sweetener sold under the trade name NutraSweet, is easily distinguishable by taste receptors from its bitter-tasting stereoisomer, although the two differ only in the configuration at one of the two chiral carbon atoms.



(*R*)-Carvone (spearmint)

(*S*)-Carvone (caraway)

(a)



L-Aspartyl-L-phenylalanine methyl ester (aspartame) (sweet)

L-Aspartyl-D-phenylalanine methyl ester (bitter)

(b)

3. Physical Foundations

3. Physical Foundations

Organisms Transform Energy and Matter from Their Surroundings

System: Every reactants and products are the contained

Universe: System plus surroundings

Isolated system: No exchange of matter, no energy with its surroundings

Closed system: Only exchange energy but no matters

Open system: Both matter and energy are exchanged: **Living system**

3. Physical Foundations

Living cells are open systems.

They exchange matter and energy with their surroundings

They extract and channelize energy to maintain themselves in a dynamic steady state.

Ultimately their energy is obtained from sunlight or chemical fuels by converting the energy from electron flow into the chemical bonds of ATP.

Living Organisms Exist in a Dynamic Steady State, Never at Equilibrium with Their Surroundings

3. Physical Foundations

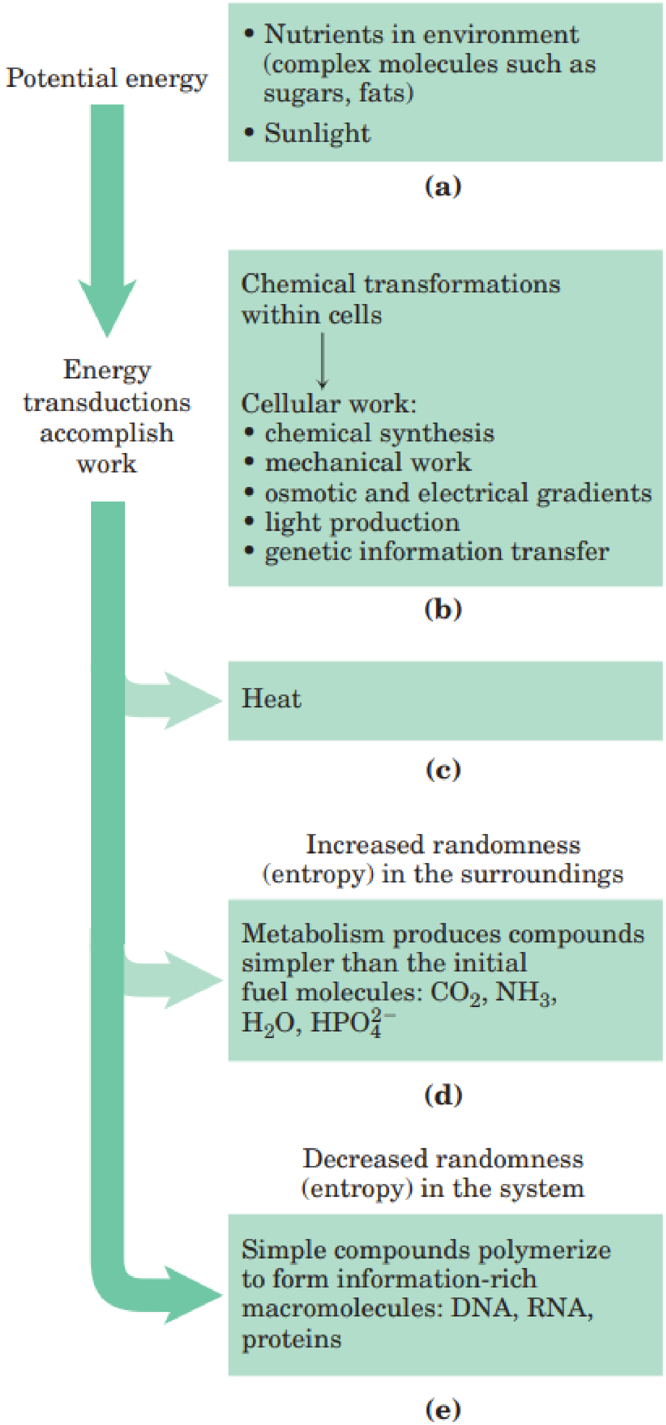
The first law of thermodynamics, developed from physics and chemistry but fully valid for biological systems as well, describes the principle of the conservation of energy:

The first law of thermodynamics : “**In any physical or chemical change, the total amount of energy in the universe remains constant, although the form of the energy may change.”**

3. Physical Foundations

The Flow of Electrons Provides Energy for Organisms

FIGURE 1–24 Some energy interconversion in living organisms. During metabolic energy transductions, the randomness of the system plus surroundings (expressed quantitatively as entropy) increases as the potential energy of complex nutrient molecules decreases. **(a)** Living organisms extract energy from their surroundings; **(b)** convert some of it into useful forms of energy to produce work; **(c)** return some energy to the surroundings as heat; and **(d)** release end-product molecules that are less well organized than the starting fuel, increasing the entropy of the universe. One effect of all these transformations is **(e)** increased order (decreased randomness) in the system in the form of complex macromolecules. We return to a quantitative treatment of entropy in Chapter 13.



3. Physical Foundations

$$6CO_2 + 6H_2O \xrightarrow{\text{light}} C_6H_{12}O_6 + 6O_2$$

(light-driven reduction of CO_2)

$$C_6H_{12}O_6 + O_2 \longrightarrow 6CO_2 + 6H_2O + \text{energy}$$

(energy-yielding oxidation of glucose)

All these reactions involving electron flow are oxidation reduction reactions:

one reactant is oxidized (loses electrons) as another is reduced (gains electrons).

3. Physical Foundations

Creating and Maintaining Order Requires Work and Energy

The second law of thermodynamics, the tendency in nature is toward ever-greater disorder in the universe:

The second law of thermodynamics: **The total entropy of the universe is continually increasing.**

3. Physical Foundations

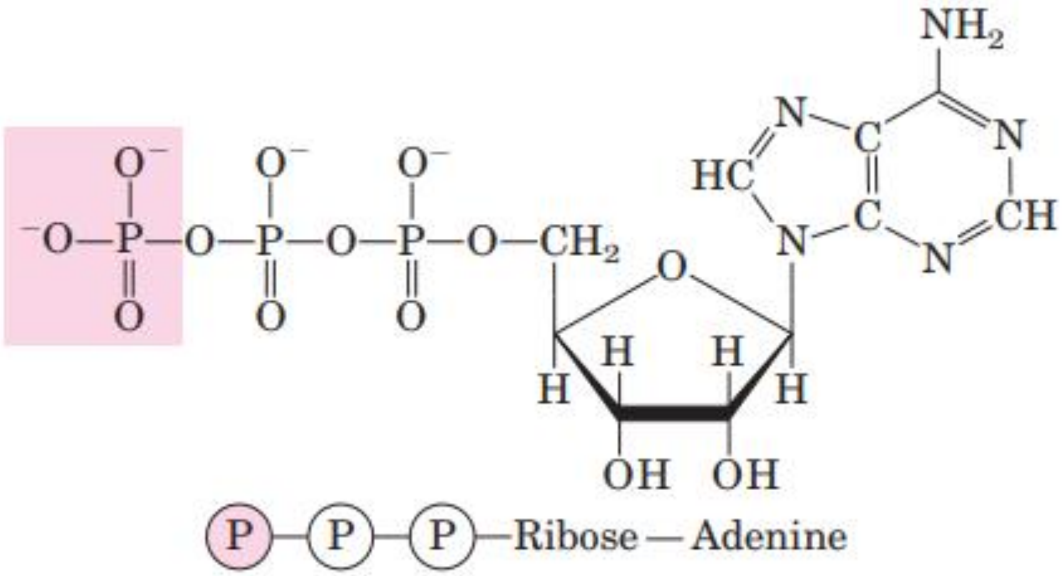


FIGURE 1–25 Adenosine triphosphate (ATP). The removal of the terminal phosphoryl group (shaded pink) of ATP, by breakage of a phosphoanhydride bond, is highly exergonic, and this reaction is coupled to many endergonic reactions in the cell (as in the example in Fig. 1–26b).

3. Physical Foundations

Entropy: The randomness or disorder of the components of a chemical system is expressed as entropy, S

Free energy content, G,
Enthalpy, H, number and kinds of bonds
Absolute Temperature T (in degrees Kelvin).

The definition of free energy of a closed system is *G = H - TS*.

Free Energy Change: ΔG

The tendency for a chemical reaction to proceed toward equilibrium can be expressed as the free-energy change, ΔG

It has two components:

Enthalpy change, ΔH, and Entropy change, ΔS.

These variables are related by the equation $\Delta G = \Delta H - T\,\Delta S.$

3. Physical Foundations

How to know which way a reaction might proceed?

If ΔG of a reaction is negative, the reaction is exergonic and tends to go toward completion

If ΔG is positive, the reaction is endergonic and tends to go in the reverse direction.

When two reactions can be summed to yield a third reaction, the ΔG for this overall reaction is the sum of the ΔGs of the two separate reactions.

This provides a way to couple reactions.

3. Physical Foundations

$$\text{Amino acids} \longrightarrow \text{polymer} \qquad \Delta G_1 \text{ is positive (endergonic)}$$

$$-P-P \longrightarrow -P + P \qquad \Delta G_2 \text{ is negative (exergonic)}$$

3. Physical Foundations

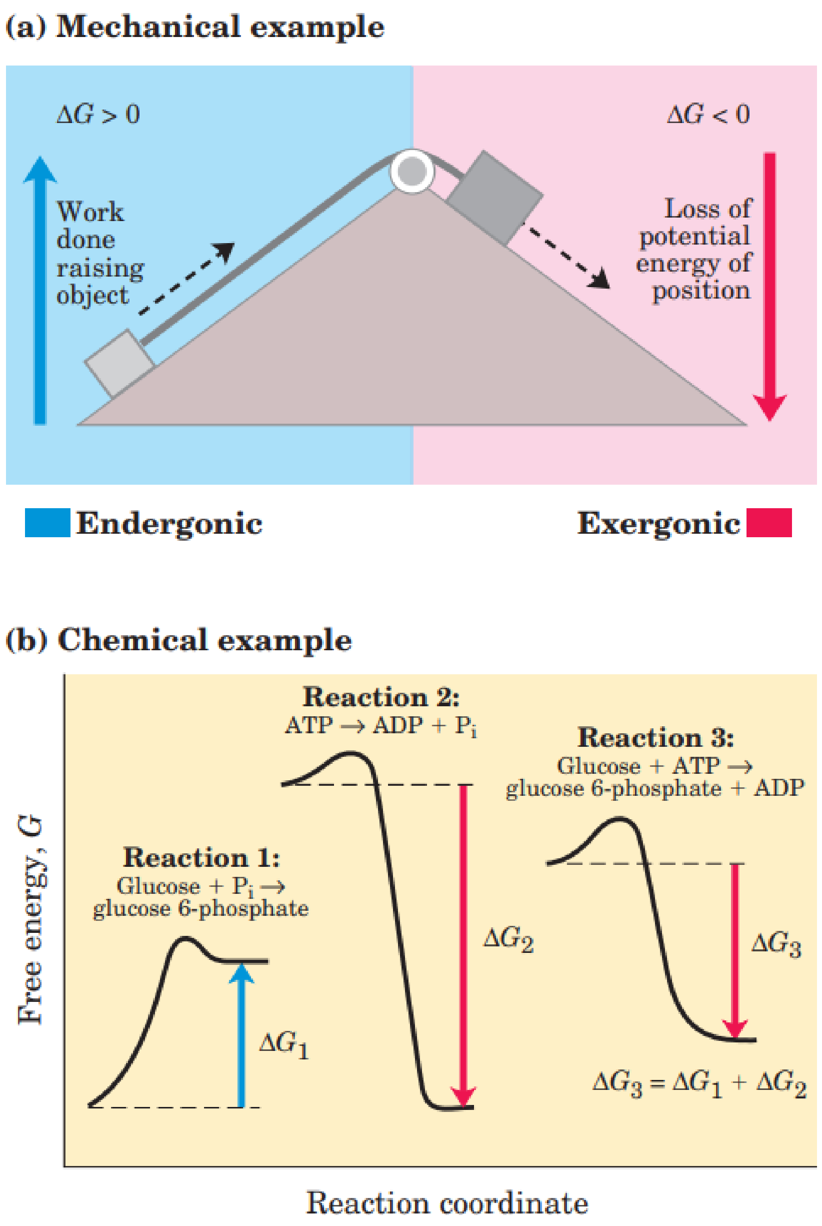


FIGURE 1–26 Energy coupling in mechanical and chemical processes. **(a)** The downward motion of an object releases potential energy that can do mechanical work. The potential energy made available by spontaneous downward motion, an exergonic process (pink), can be coupled to the endergonic upward movement of another object (blue). **(b)** In reaction 1, the formation of glucose 6-phosphate from glucose and inorganic phosphate (P_i) yields a product of higher energy than the two reactants. For this endergonic reaction, ΔG is positive. In reaction 2, the exergonic breakdown of adenosine triphosphate (ATP) can drive an endergonic reaction when the two reactions are coupled. The exergonic reaction has a large, negative free-energy change (ΔG_2), and the endergonic reaction has a smaller, positive free-energy change (ΔG_1). The third reaction accomplishes the sum of reactions 1 and 2, and the free-energy change, ΔG_3, is the arithmetic sum of ΔG_1 and ΔG_2. Because ΔG_3 is negative, the overall reaction is exergonic and proceeds spontaneously.

3. Physical Foundations

Reaction 1: Glucose + $P_i \longrightarrow$ glucose 6-phosphate

(endergonic; ΔG_1 is positive)

Reaction 2: ATP $\longrightarrow$ ADP + P_i

(exergonic; ΔG_2 is negative)

Reaction 3: Glucose + ATP $\longrightarrow$

glucose 6-phosphate + ADP

3. Physical Foundations

$$aA + bB \longrightarrow cC + dD$$

The equilibrium constant, Keq

$$K_{eq} = \frac{[C_{eq}]^c[D_{eq}]^d}{[A_{eq}]^a[B_{eq}]^b}$$

When a reaction has reached equilibrium, no driving force remains and it can do no work: ΔG =0

Standard free-energy change,

$$\Delta G = \Delta G^\circ + RT \ln \frac{[C_i]^c[D_i]^d}{[A_i]^a[B_i]^b}$$

$$\Delta G^\circ = -RT \ln K_{eq}$$

$$\frac{[C_i]^c[D_i]^d}{[A_i]^a[B_i]^b} = \frac{[C_{eq}]^c[D_{eq}]^d}{[A_{eq}]^a[B_{eq}]^b} = K_{eq}$$

3. Physical Foundations

The standard free-energy change for a reaction, ΔG°,

It is a physical constant that is related to the equilibrium constant by

the equation $\Delta G^\circ = -RT \ln K_{\mathrm{eq}}.$

3. Physical Foundations

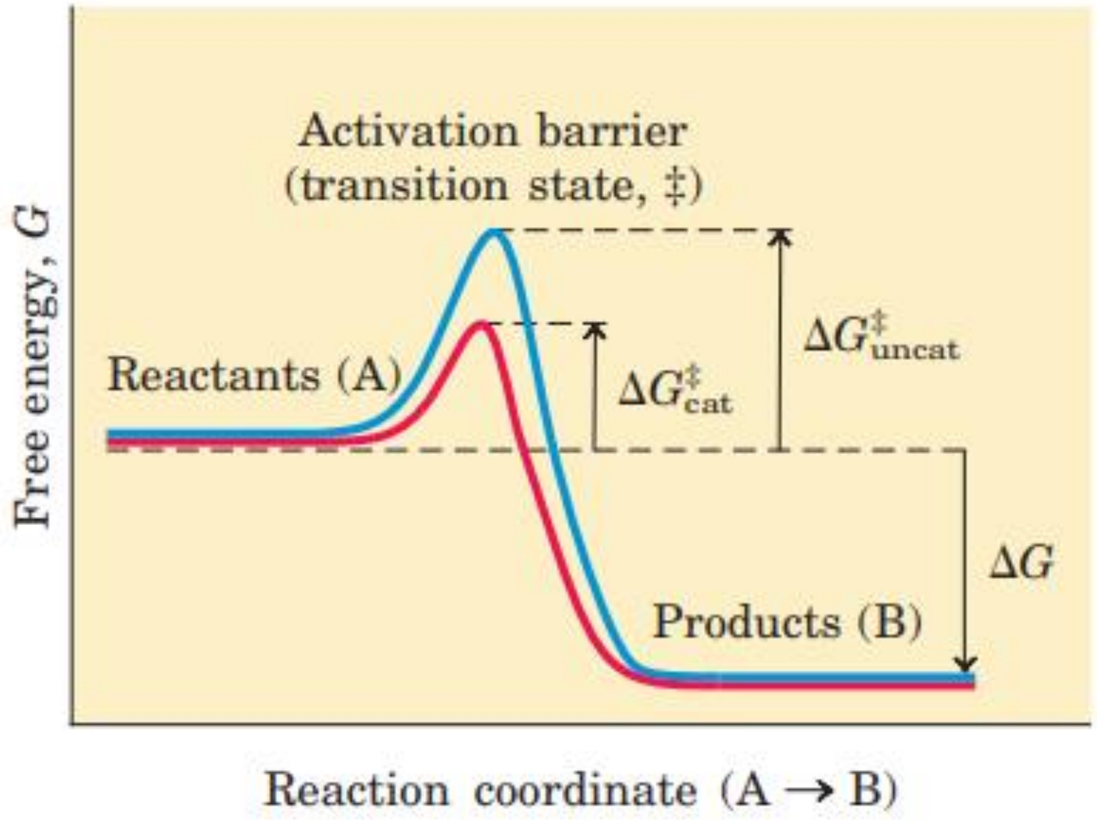


FIGURE 1–27 Energy changes during a chemical reaction. An activation barrier, representing the transition state, must be overcome in the conversion of reactants (A) into products (B), even though the products are more stable than the reactants, as indicated by a large, negative free-energy change (ΔG). The energy required to overcome the activation barrier is the activation energy ($\Delta G^{\ddagger}$). Enzymes catalyze reactions by lowering the activation barrier. They bind the transition-state intermediates tightly, and the binding energy of this interaction effectively reduces the activation energy from $\Delta G^{\ddagger}_{uncat}$ to $\Delta G^{\ddagger}_{cat}$. (Note that activation energy is *not* related to free-energy change, ΔG.)

3. Physical Foundations

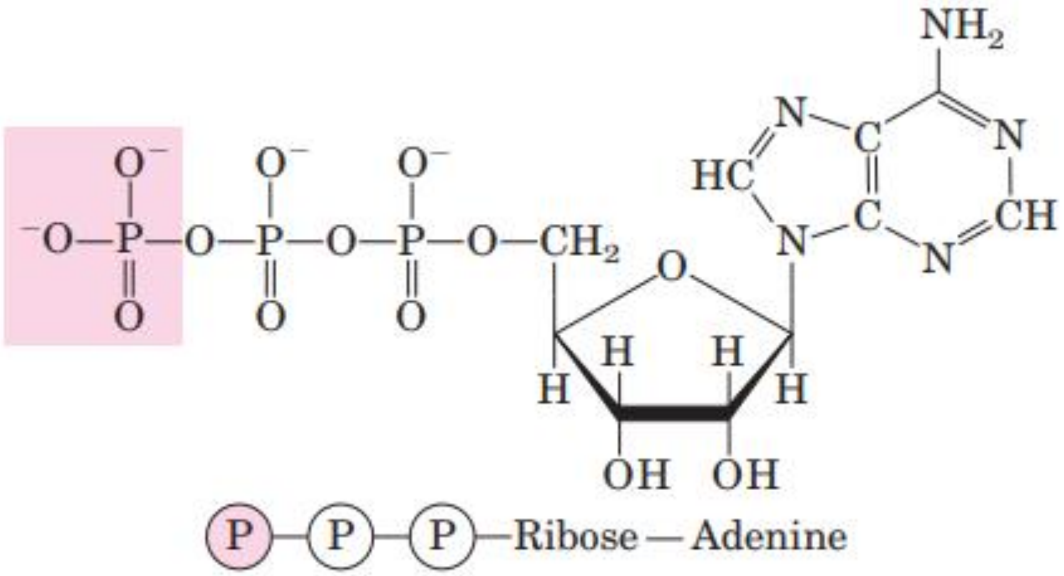


FIGURE 1–25 Adenosine triphosphate (ATP). The removal of the terminal phosphoryl group (shaded pink) of ATP, by breakage of a phosphoanhydride bond, is highly exergonic, and this reaction is coupled to many endergonic reactions in the cell (as in the example in Fig. 1–26b).

3. Physical Foundations

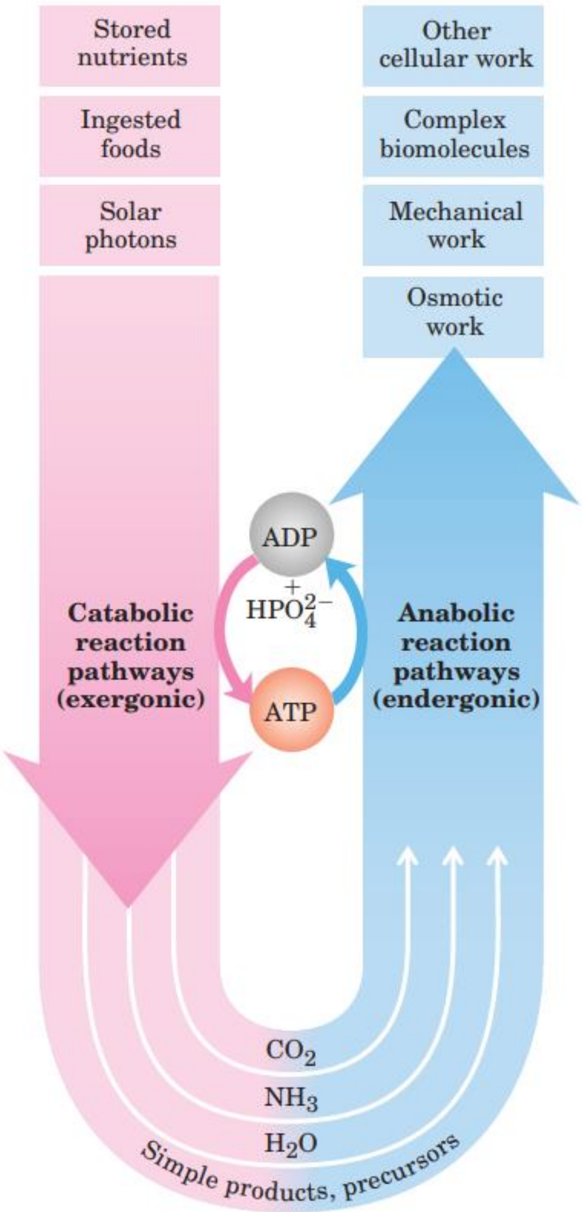
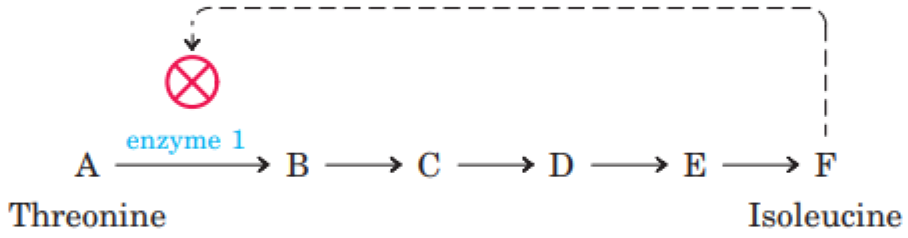


FIGURE 1–28 The central role of ATP in metabolism. ATP is the shared chemical intermediate linking energy-releasing to energy-requiring cell processes. Its role in the cell is analogous to that of money in an economy: it is "earned/produced" in exergonic reactions and "spent/consumed" in endergonic ones.

3. Physical Foundations

Metabolism Is Regulated to Achieve Balance and Economy

Feedback inhibition



4. Genetic Foundations

What is the best genetic material for the living organisms?

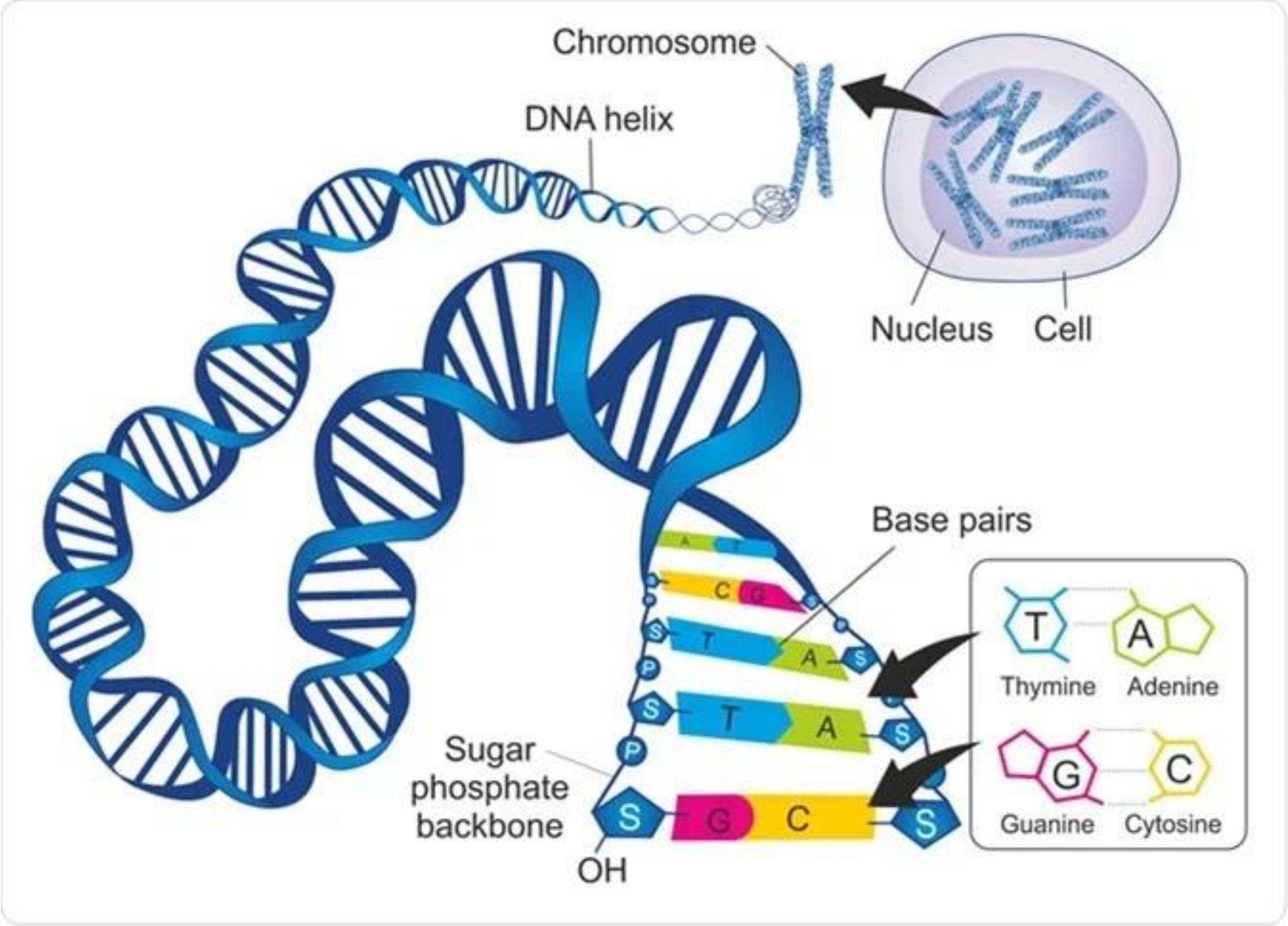
4. Genetic Foundations

(a) (b)

FIGURE 1–29 Two ancient scripts. (a) The Prism of Sennacherib, inscribed in about 700 B.C.E., describes in characters of the Assyrian language some historical events during the reign of King Sennacherib. The Prism contains about 20,000 characters, weighs about 50 kg, and has survived almost intact for about 2,700 years. **(b)** The single DNA molecule of the bacterium *E. coli,* seen leaking out of a disrupted cell, is hundreds of times longer than the cell itself and contains all the encoded information necessary to specify the cell's structure and functions. The bacterial DNA contains about 10 million characters (nucleotides), weighs less than 10^{-10} g, and has undergone only relatively minor changes during the past several million years. (The yellow spots and dark specks in this colorized electron micrograph are artifacts of the preparation.)

4. Genetic Foundations

DNA



4. Genetic Foundations

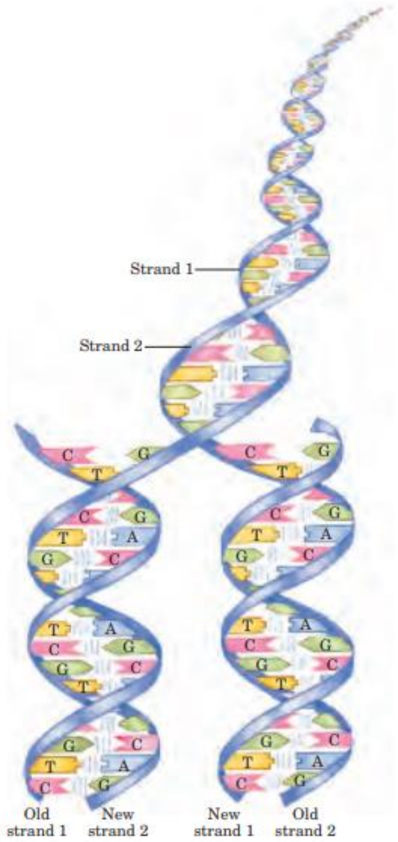


FIGURE 1–30 Complementarity between the two strands of DNA. DNA is a linear polymer of covalently joined deoxyribonucleotides, of four types: deoxyadenylate (A), deoxyguanylate (G), deoxycytidylate (C), and deoxythymidylate (T). Each nucleotide, with its unique three-dimensional structure, can associate very specifically but noncovalently with one other nucleotide in the complementary chain: A always associates with T, and G with C. Thus, in the double-stranded DNA molecule, the entire sequence of nucleotides in one strand is *complementary* to the sequence in the other. The two strands, held together by hydrogen bonds (represented here by vertical blue lines) between each pair of complementary nucleotides, twist about each other to form the DNA double helix. In DNA replication, the two strands separate and two new strands are synthesized, each with a sequence complementary to one of the original strands. The result is two double-helical molecules, each identical to the original DNA.

4. Genetic Foundations

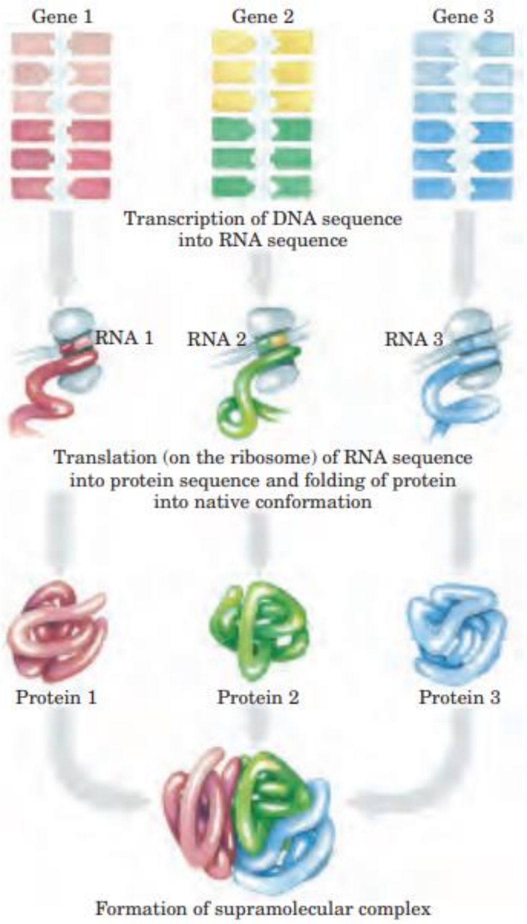
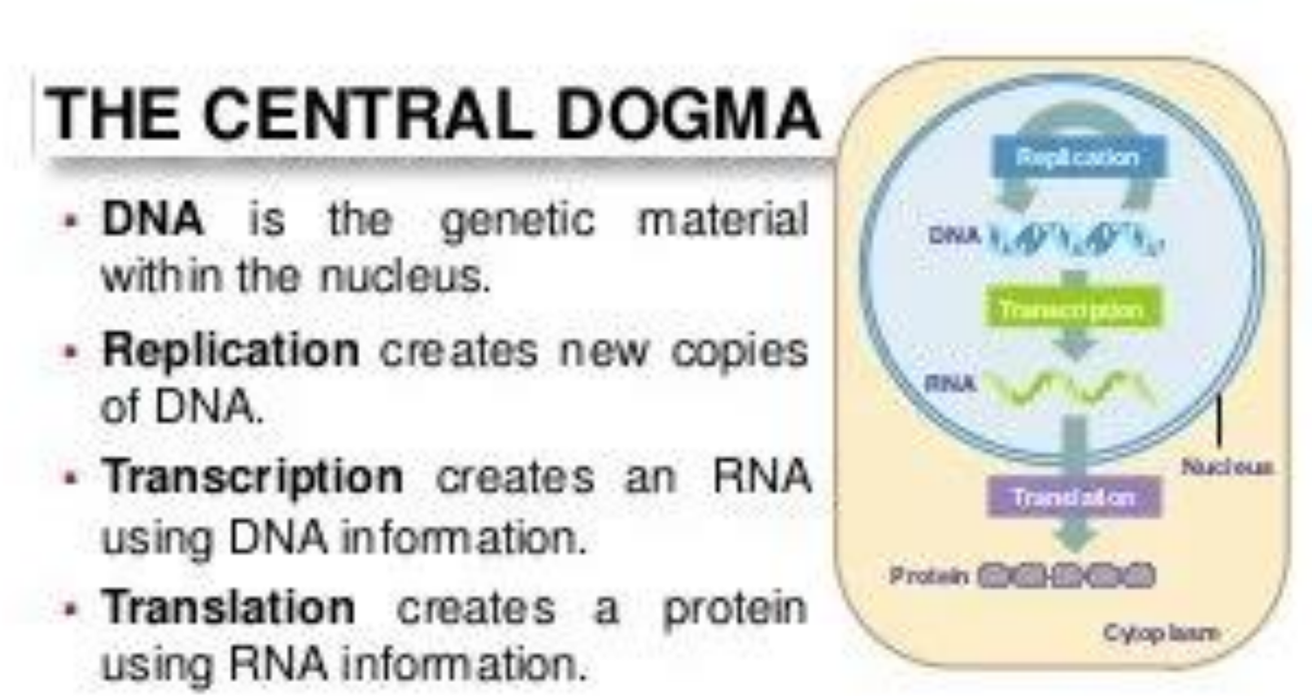


FIGURE 1–31 DNA to RNA to protein. Linear sequences of deoxyribonucleotides in DNA, arranged into units known as genes, are transcribed into ribonucleic acid (RNA) molecules with complementary ribonucleotide sequences. The RNA sequences are then translated into linear protein chains, which fold into their native three-dimensional shapes, often aided by molecular chaperones. Individual proteins commonly associate with other proteins to form supramolecular complexes, stabilized by numerous weak interactions.

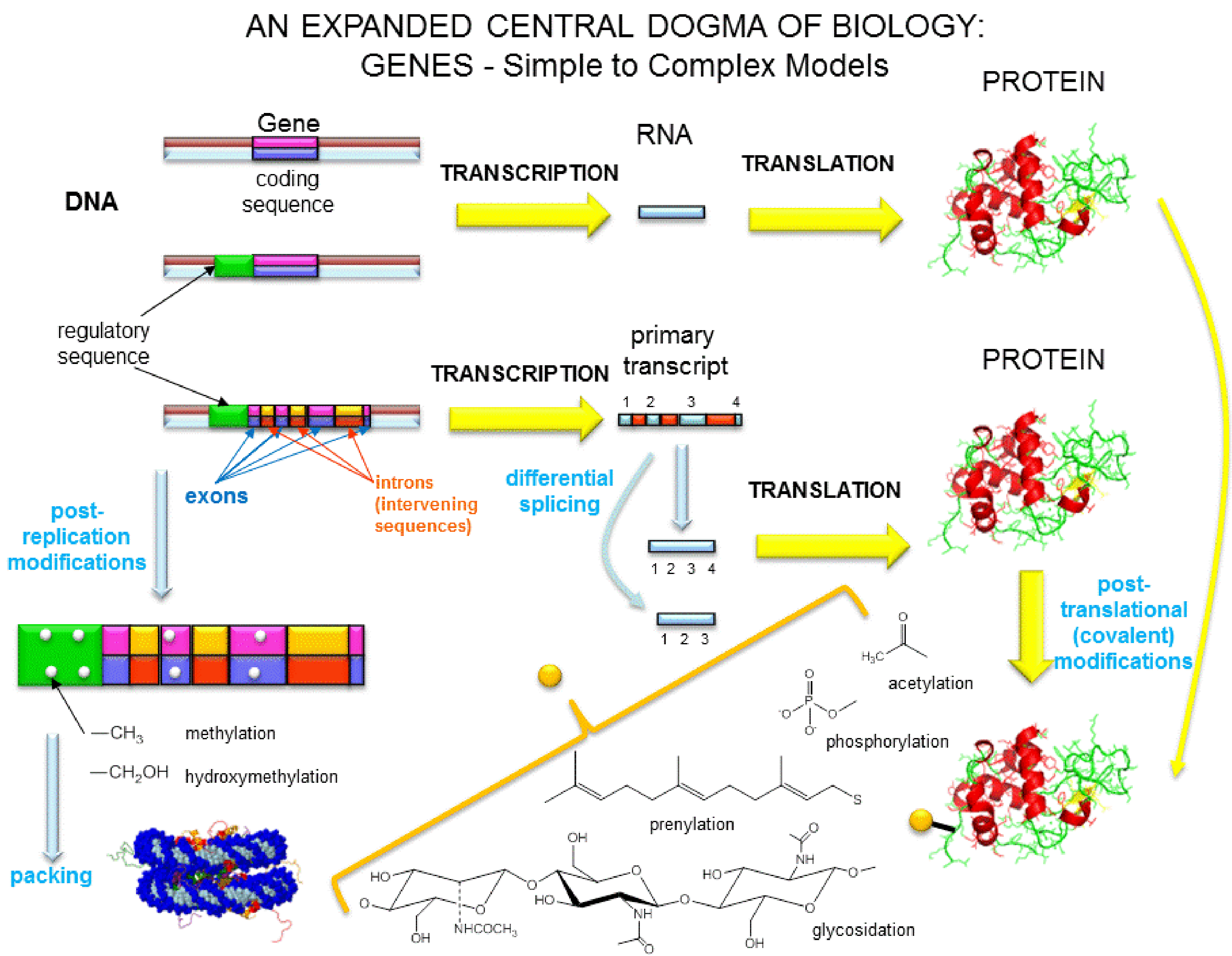
4. Genetic Foundations



4. Genetic Foundations

4. Genetic Foundations

Biochemistry



5. Evolutionary Foundations

Nothing in biology makes sense except in the light of evolution.

—Theodosius Dobzhansky, The American Biology Teacher, March 1973

5. Evolutionary Foundations

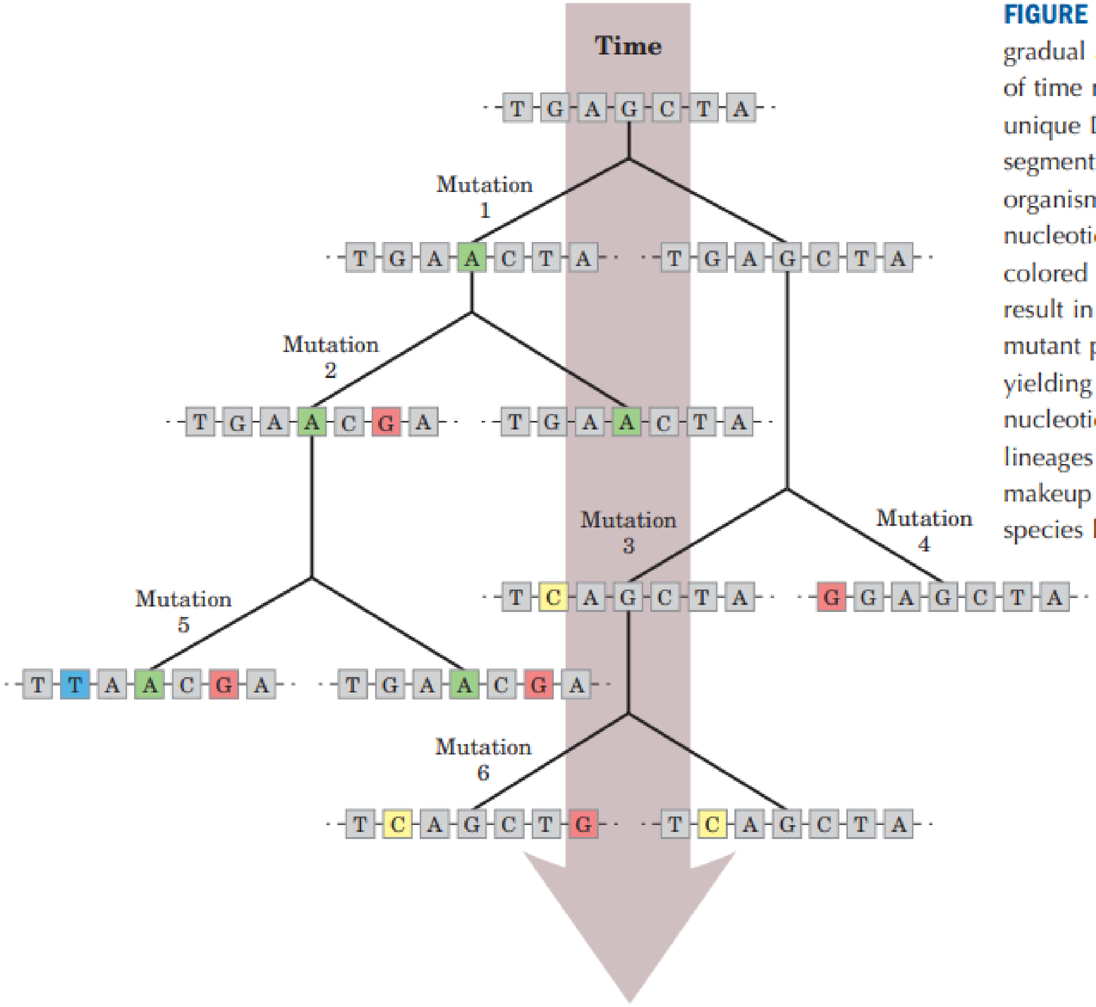


FIGURE 1–32 Role of mutation in evolution. The gradual accumulation of mutations over long periods of time results in new biological species, each with a unique DNA sequence. At the top is shown a short segment of a gene in a hypothetical progenitor organism. With the passage of time, changes in nucleotide sequence (mutations, indicated here by colored boxes), *occurring one nucleotide at a time*, result in progeny with different DNA sequences. These mutant progeny also undergo occasional mutations, yielding their own progeny that differ by two or more nucleotides from the progenitor sequence. When two lineages have diverged so much in their genetic makeup that they can no longer interbreed, a new species has been created.

5. Evolutionary Foundations

Biomolecules First Arose by Chemical Evolution

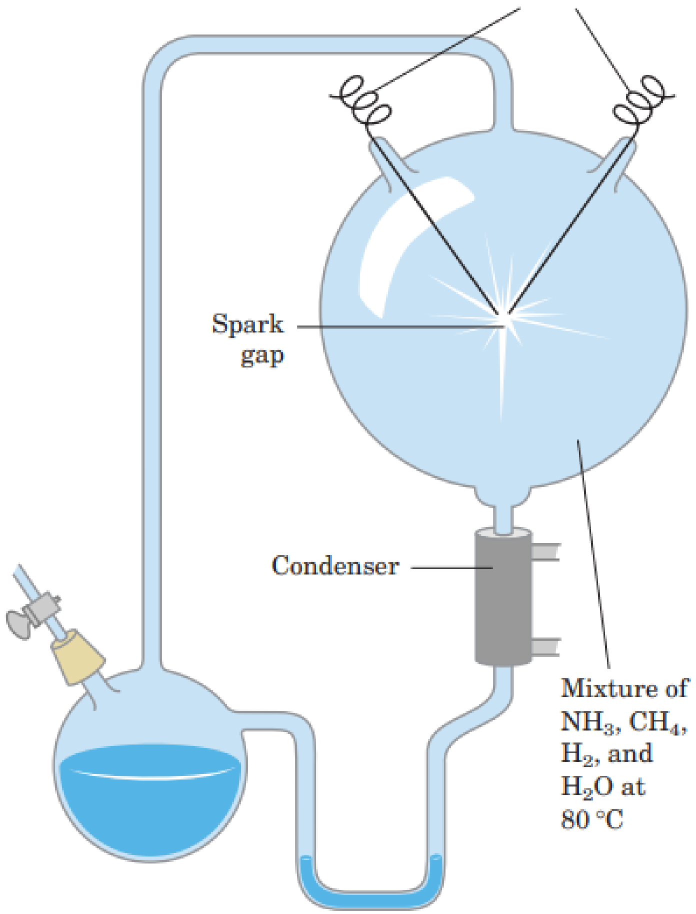


FIGURE 1–33 Abiotic production of biomolecules. Spark-discharge apparatus of the type used by Miller and Urey in experiments demonstrating abiotic formation of organic compounds under primitive atmospheric conditions. After subjection of the gaseous contents of the system to electrical sparks, products were collected by condensation. Biomolecules such as amino acids were among the products.

5. Evolutionary Foundations

Biological Evolution Began More

Than Three and a Half Billion Years Ago

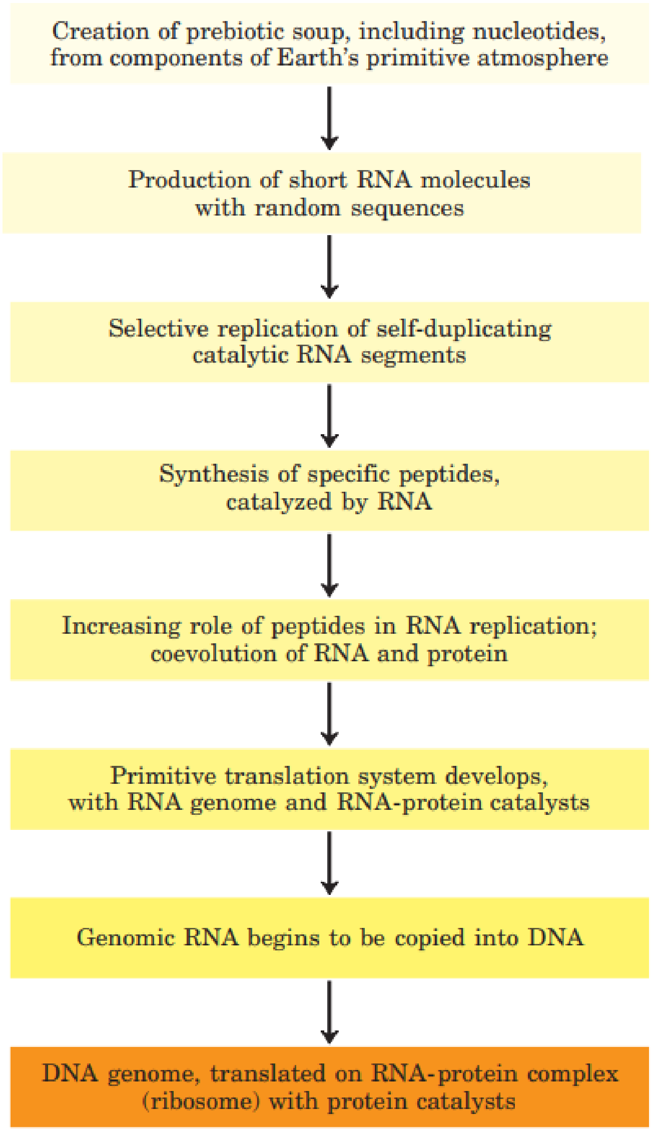


FIGURE 1–34 A possible “RNA world” scenario.

5. Evolutionary Foundations

Biological Evolution Began More

Than Three and a Half Billion Years Ago

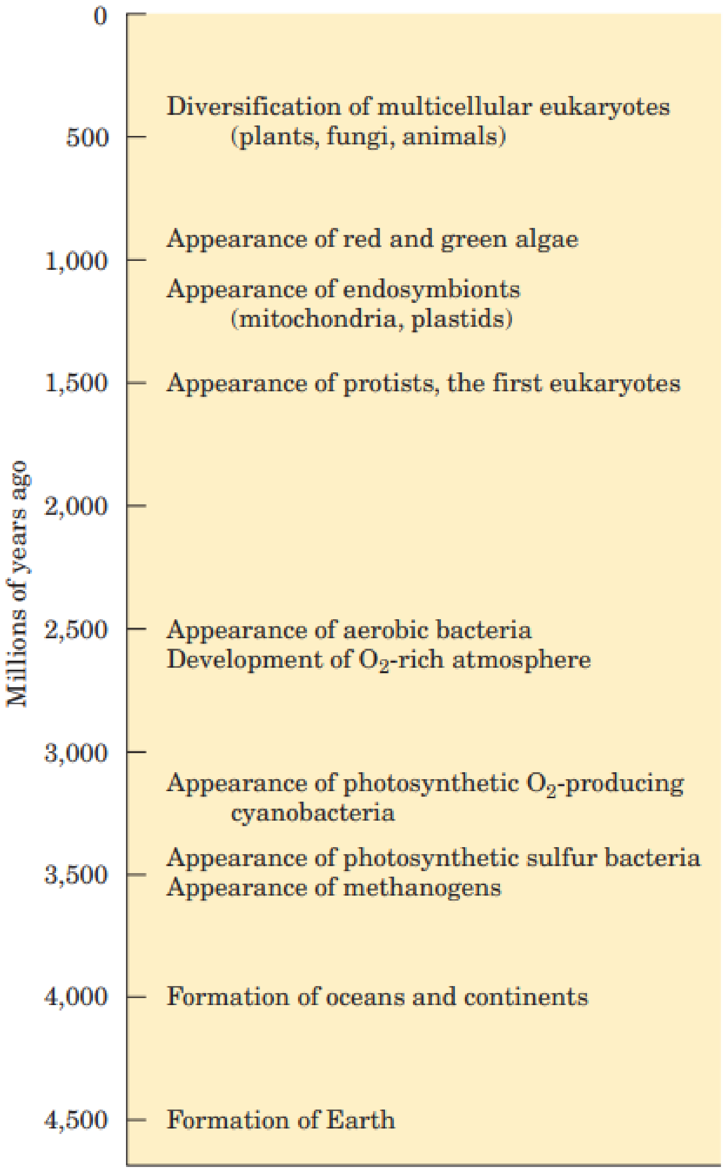


FIGURE 1–35 Landmarks in the evolution of life on Earth.

The First Cell Was Probably a Chemoheterotroph

Eukaryotic Cells Evolved from Prokaryotes in Several Stages

5. Evolutionary Foundations

Eukaryotic Cells Evolved from Prokaryotes
in Several Stages

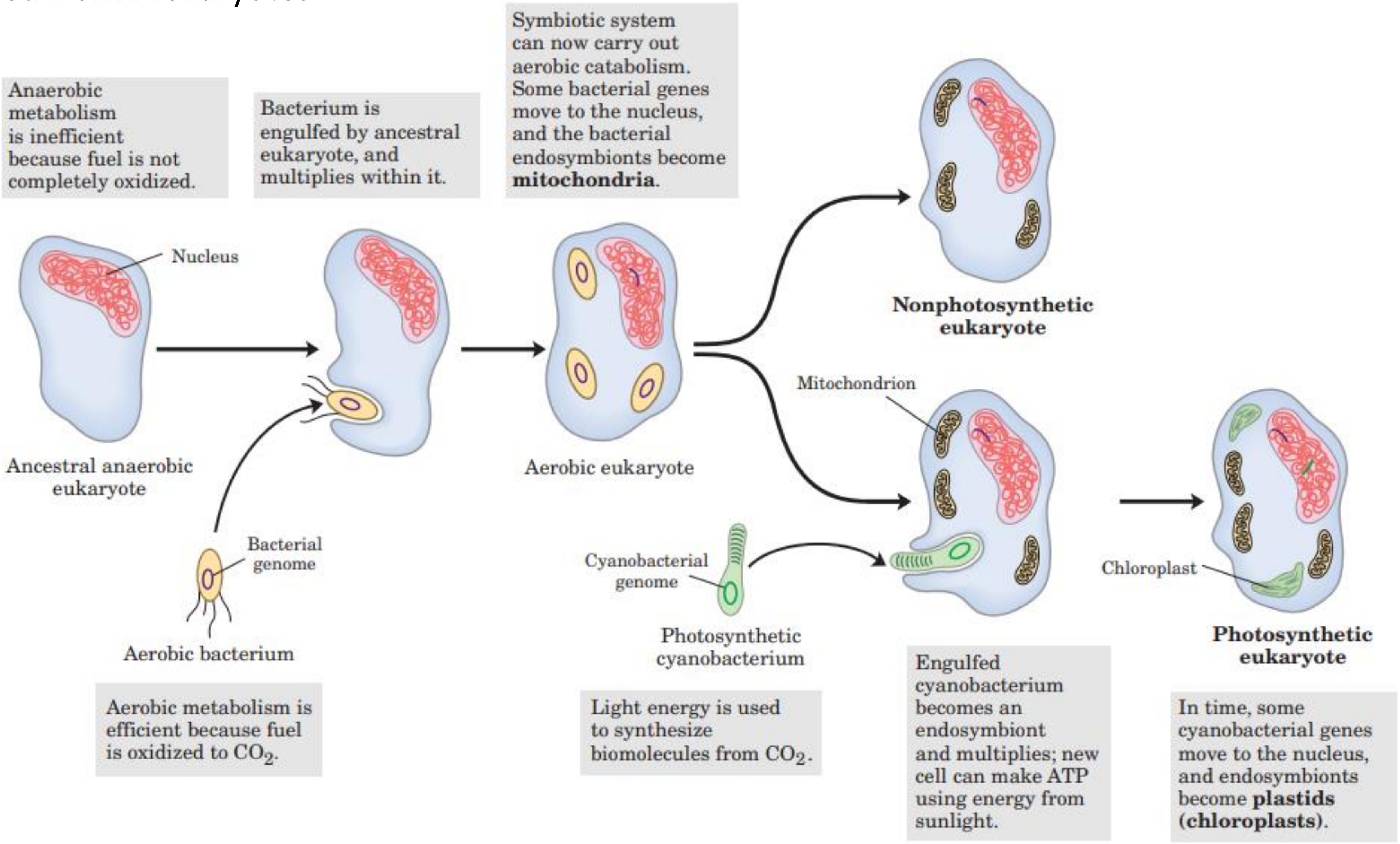


FIGURE 1–36 Evolution of eukaryotes through endosymbiosis. The earliest eukaryote, an anaerobe, acquired endosymbiotic purple bacteria (yellow), which carried with them their capacity for aerobic catabolism and became, over time, mitochondria. When photosynthetic cyanobacteria (green) subsequently became endosymbionts of some aerobic eukaryotes, these cells became the photosynthetic precursors of modern green algae and plants.

5. Evolutionary Foundations

TABLE 1–3 Comparison of Prokaryotic and Eukaryotic Cells

Characteristic	*Prokaryotic cell*	*Eukaryotic cell*
Size	Generally small (1–10 μm)	Generally large (5–100 μm)
Genome	DNA with nonhistone protein; genome in nucleoid, not surrounded by membrane	DNA complexed with histone and nonhistone proteins in chromosomes; chromosomes in nucleus with membranous envelope
Cell division	Fission or budding; no mitosis	Mitosis, including mitotic spindle; centrioles in many species
Membrane-bounded organelles	Absent	Mitochondria, chloroplasts (in plants, some algae), endoplasmic reticulum, Golgi complexes, lysosomes (in animals), etc.
Nutrition	Absorption; some photosynthesis	Absorption, ingestion; photosynthesis in some species
Energy metabolism	No mitochondria; oxidative enzymes bound to plasma membrane; great variation in metabolic pattern	Oxidative enzymes packaged in mitochondria; more unified pattern of oxidative metabolism
Cytoskeleton	None	Complex, with microtubules, intermediate filaments, actin filaments
Intracellular movement	None	Cytoplasmic streaming, endocytosis, phagocytosis, mitosis, vesicle transport

Source: Modified from Hickman, C.P., Roberts, L.S., & Hickman, F.M. (1990) *Biology of Animals*, 5th edn, p. 30, Mosby-Yearbook, Inc., St. Louis, MO.

5. Evolutionary Foundations

TABLE 1–4 Some Organisms Whose Genomes Have Been Completely Sequenced

Organism	*Genome size (millions of nucleotide pairs)*	*Biological interest*
Mycoplasma pneumoniae	0.8	Causes pneumonia
Treponema pallidum	1.1	Causes syphilis
Borrelia burgdorferi	1.3	Causes Lyme disease
Helicobacter pylori	1.7	Causes gastric ulcers
Methanococcus jannaschii	1.7	Grows at 85 °C!
Haemophilus influenzae	1.8	Causes bacterial influenza
Methanobacterium thermoautotrophicum	1.8	Member of the Archaea
Archaeoglobus fulgidus	2.2	High-temperature methanogen
Synechocystis sp.	3.6	Cyanobacterium
Bacillus subtilis	4.2	Common soil bacterium
Escherichia coli	4.6	Some strains cause toxic shock syndrome
Saccharomyces cerevisiae	12.1	Unicellular eukaryote
Plasmodium falciparum	23	Causes human malaria
Caenorhabditis elegans	97.1	Multicellular roundworm
Anopheles gambiae	278	Malaria vector
Mus musculus domesticus	2.5×10^3	Laboratory mouse
Homo sapiens	2.9×10^3	Human

5. Evolutionary Foundations

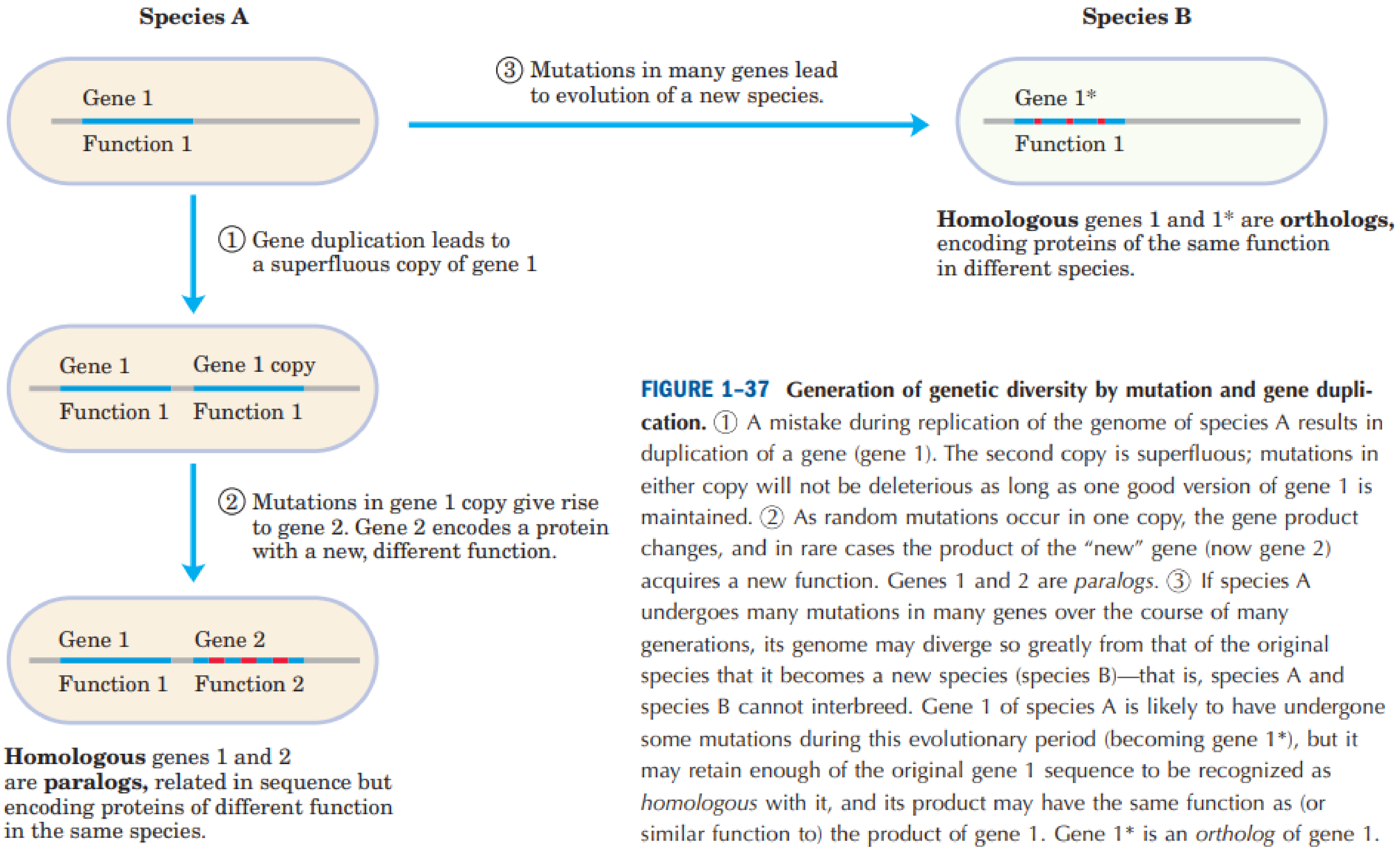


FIGURE 1–37 Generation of genetic diversity by mutation and gene duplication. ① A mistake during replication of the genome of species A results in duplication of a gene (gene 1). The second copy is superfluous; mutations in either copy will not be deleterious as long as one good version of gene 1 is maintained. ② As random mutations occur in one copy, the gene product changes, and in rare cases the product of the "new" gene (now gene 2) acquires a new function. Genes 1 and 2 are *paralogs*. ③ If species A undergoes many mutations in many genes over the course of many generations, its genome may diverge so greatly from that of the original species that it becomes a new species (species B)—that is, species A and species B cannot interbreed. Gene 1 of species A is likely to have undergone some mutations during this evolutionary period (becoming gene 1*), but it may retain enough of the original gene 1 sequence to be recognized as *homologous* with it, and its product may have the same function as (or similar function to) the product of gene 1. Gene 1* is an *ortholog* of gene 1.