Alberts • Johnson • Lewis • Morgan • Raff • Roberts • Walter

Molecular Biology of the Cell

Sixth Edition

Chapter 1
Cells and Genomes

CHAPTER CONTENTS

THE UNIVERSAL FEATURES OF CELLS ON EARTH

Introduction

Introduction

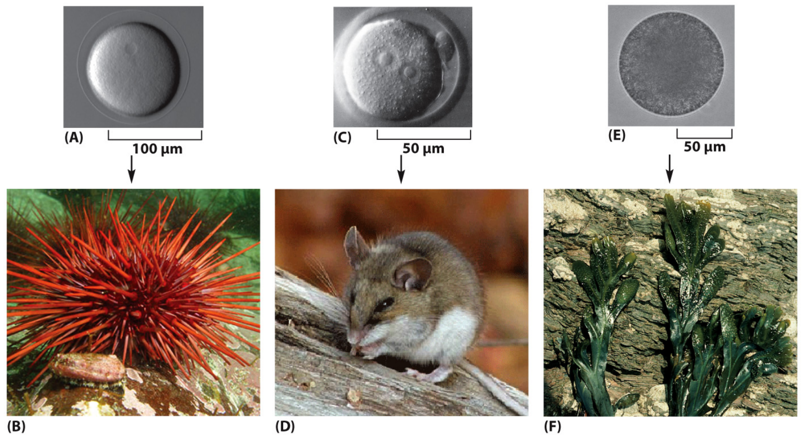


Figure 1-1 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–1 The hereditary information in the fertilized egg cell determines the nature of the whole multicellular organism. Although their starting cells look superficially similar, as indicated: a sea urchin egg gives rise to a sea urchin (A and B). A mouse egg gives rise to a mouse (C and D). An egg of the seaweed *Fucus* gives rise to a *Fucus* seaweed (E and F).

THE UNIVERSAL FEATURES OF CELLS ON EARTH

All Cells Store Their Hereditary Information in the Same Linear Chemical Code: DNA

THE UNIVERSAL FEATURES OF CELLS ON EARTH

All Cells Replicate Their Hereditary Information by Templated Polymerization

All Cells Replicate Their Hereditary Information by Templated Polymerization

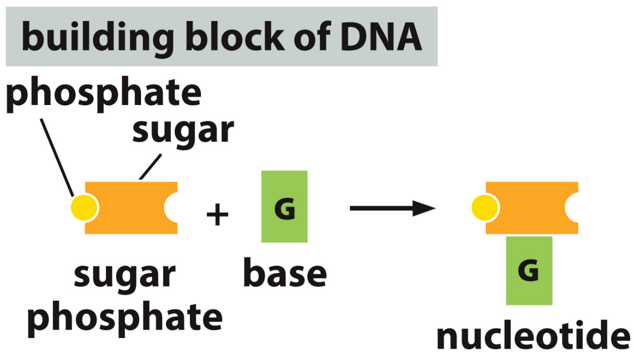


Figure 1-2a Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–2 DNA and its building blocks. (A) DNA is made from simple subunits, called nucleotides, each consisting of a sugar-phosphate molecule with a nitrogen- containing side group, or base, attached to it. The bases are of four types (adenine, guanine, cytosine, and thymine), corresponding to four distinct nucleotides, labeled A, G, C, and T.

All Cells Replicate Their Hereditary Information by Templated Polymerization

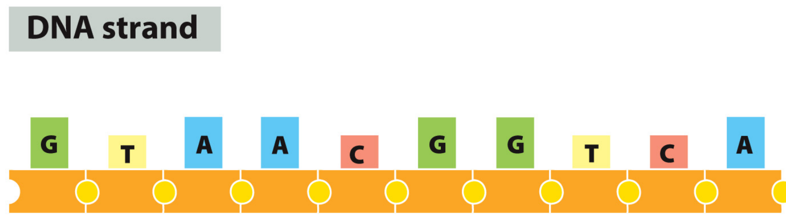


Figure 1-2b Molecular Biology of the Cell 6e (© Garland Science 2015)

(B) A single strand of DNA consists of nucleotides joined together by sugar- phosphate linkages. Note that the individual sugar-phosphate units are asymmetric, giving the backbone of the strand a definite directionality, or polarity. This directionality guides the molecular processes by which the information in DNA is interpreted and copied in cells: the information is always “read” in a consistent order, just as written English text is read from left to right.

All Cells Replicate Their Hereditary Information by Templated Polymerization

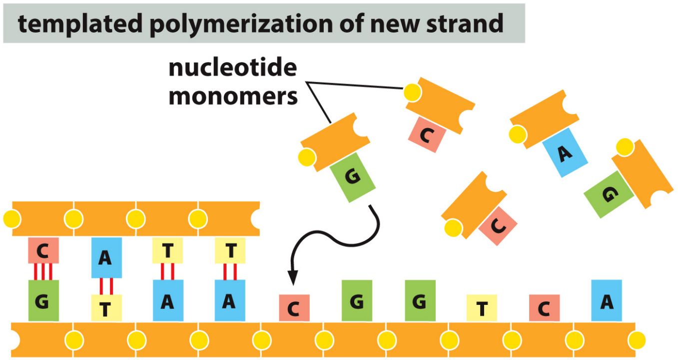


Figure 1-2c Molecular Biology of the Cell 6e (© Garland Science 2015)

(C) Through templated polymerization, the sequence of nucleotides in an existing DNA strand controls the sequence in which nucleotides are joined together in a new DNA strand; T in one strand pairs with A in the other, and G in one strand with C in the other. The new strand has a nucleotide sequence *complementary* to that of the old strand, and a backbone with opposite directionality: corresponding to the GTAA... of the original strand, it has ...TTAC.

All Cells Replicate Their Hereditary Information by Templated Polymerization

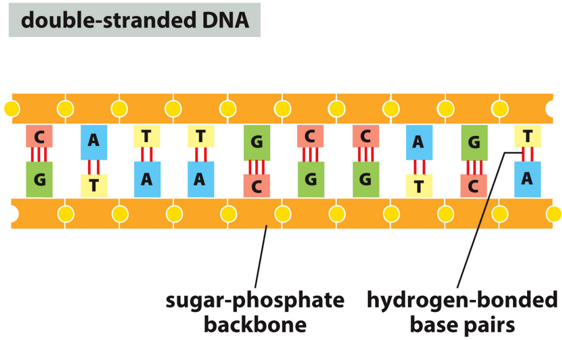


Figure 1-2d Molecular Biology of the Cell 6e (© Garland Science 2015)

(D) A normal DNA molecule consists of two such complementary strands. The nucleotides within each strand are linked by strong (covalent) chemical bonds; the complementary nucleotides on opposite strands are held together more weakly, by hydrogen bonds.

All Cells Replicate Their Hereditary Information by Templated Polymerization

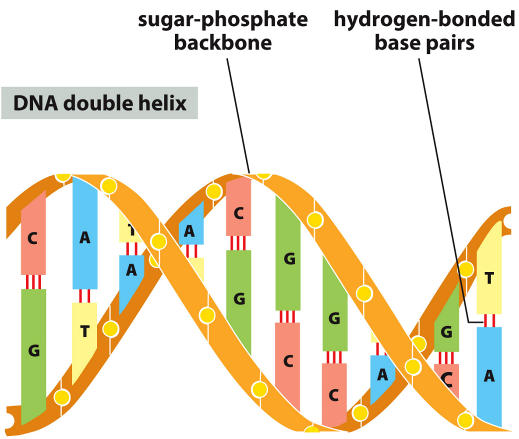


Figure 1-2e Molecular Biology of the Cell 6e (© Garland Science 2015)

(E) The two strands twist around each other to form a double helix—a robust structure that can accommodate any sequence of nucleotides without altering its basic structure (see Movie 4.1).

All Cells Replicate Their Hereditary Information by Templated Polymerization

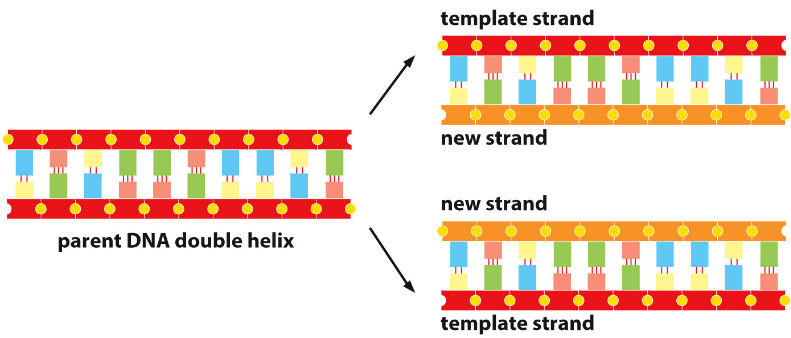


Figure 1-3 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–3 The copying of genetic information by DNA replication. In this process, the two strands of a DNA double helix are pulled apart, and each serves as a template for synthesis of a new complementary strand.

THE UNIVERSAL FEATURES OF CELLS ON EARTH

All Cells Transcribe Portions of Their Hereditary Information into the Same Intermediary Form: RNA

\

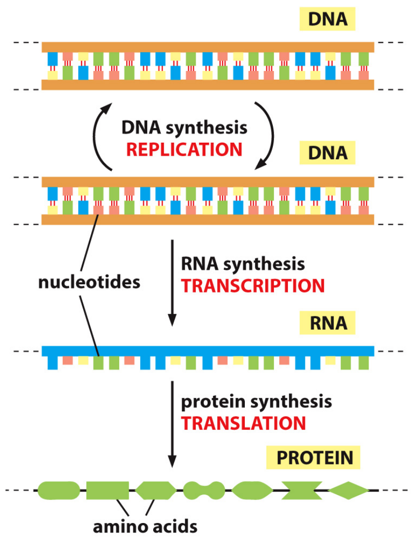


Figure 1-4 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–4 From DNA to protein. Genetic information is read out and put to use through a two-step process. First, in *transcription*, segments of the DNA sequence are used to guide the synthesis of molecules of RNA. Then, in *translation*, the RNA molecules are used to guide the synthesis of molecules of protein.

All Cells Transcribe Portions of Their Hereditary Information into the Same Intermediary Form: RNA

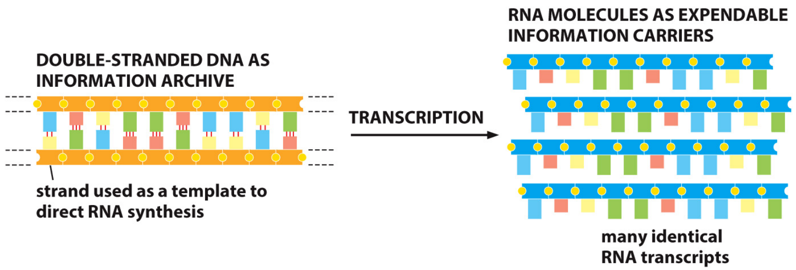


Figure 1-5 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–5 How genetic information is broadcast for use inside the cell. Each cell contains a fixed set of DNA molecules—its archive of genetic information. A given segment of this DNA guides the synthesis of many identical RNA transcripts, which serve as working copies of the information stored in the archive. Many different sets of RNA molecules can be made by transcribing different parts of a cell's DNA sequences, allowing different types of cells to use the same information store differently.

All Cells Transcribe Portions of Their Hereditary Information into the Same Intermediary Form: RNA

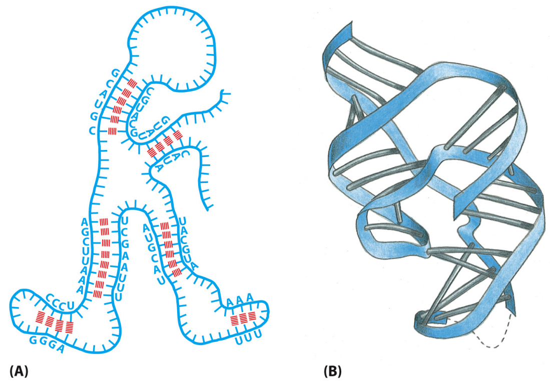


Figure 1-6 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–6 The conformation of an RNA molecule. (A) Nucleotide pairing between different regions of the same RNA polymer chain causes the molecule to adopt a distinctive shape. (B) The three-dimensional structure of an actual RNA molecule produced by hepatitis delta virus; this RNA can catalyze RNA strand cleavage. The *blue* ribbon represents the sugar-phosphate backbone and the bars represent base pairs (see Movie 6.1). (B, based on A.R. Ferré-D'Amaré, K. Zhou, and J.A. Doudna, *Nature* 395:567–574, 1998. With permission from Macmillan Publishers Ltd.)

THE UNIVERSAL FEATURES
OF CELLS ON EARTH

All Cells Use Proteins as Catalysts

All Cells Use Proteins as Catalysts

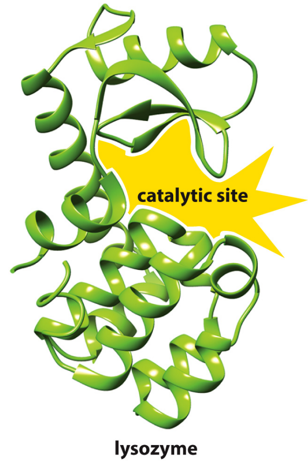


Figure 1–7 How a protein molecule acts as a catalyst for a chemical reaction. (A) In a protein molecule, the polymer chain folds up into a specific shape defined by its amino acid sequence. A groove in the surface of this particular folded molecule, the enzyme lysozyme, forms a catalytic site.

All Cells Use Proteins as Catalysts

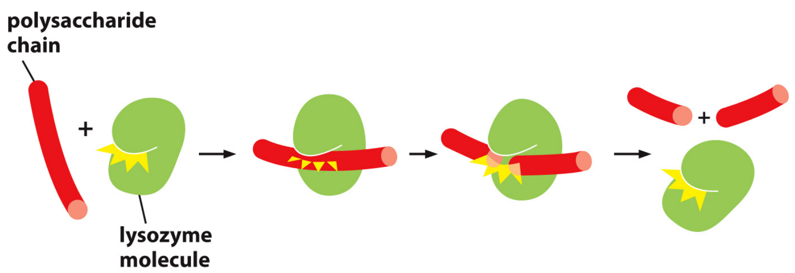
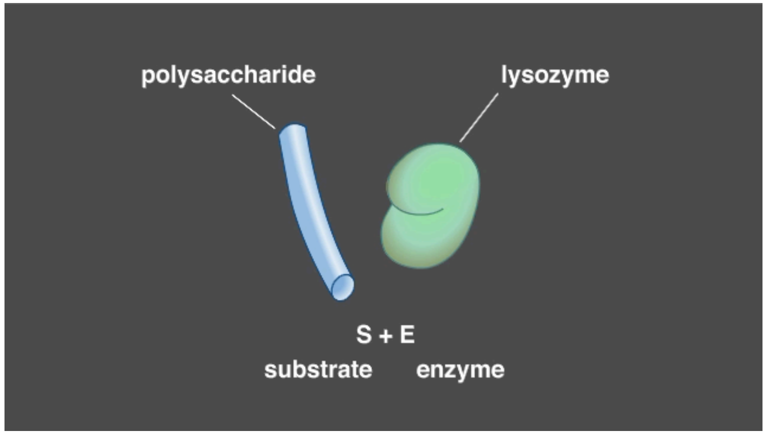


Figure 1-7b Molecular Biology of the Cell 6e (© Garland Science 2015)

(B) A polysaccharide molecule *(red)*—a polymer chain of sugar monomers—binds to the catalytic site of lysozyme and is broken apart, as a result of a covalent bond-breaking reaction catalyzed by the amino acids lining the groove (see Movie 3.9). (PDB code: 1LYD.)

All Cells Use Proteins as Catalysts



03.9_Lysozyme_Reaction

All Cells Use Proteins as Catalysts

https://www.rcsb.org/structure/1LYD

All Cells Use Proteins as Catalysts

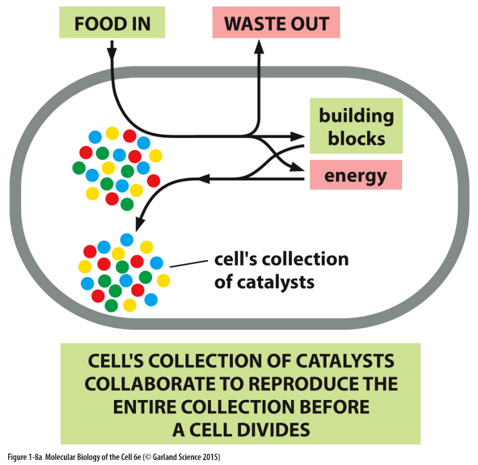
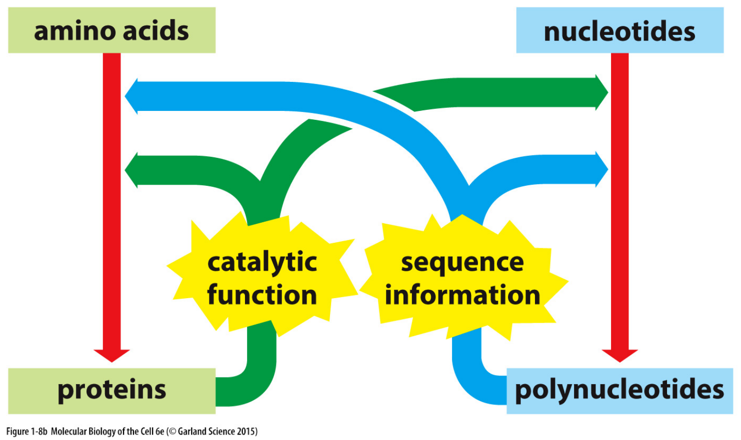


Figure 1–8 Life as an autocatalytic process. (A) The cell as a self-replicating collection of catalysts.

All Cells Use Proteins as Catalysts



(B) Polynucleotides (the nucleic acids DNA and RNA, which are nucleotide polymers) provide the sequence information, while proteins (amino acid polymers) provide most of the catalytic functions that serve—through a complex set of chemical reactions—to bring about the synthesis of more polynucleotides and proteins of the same types.

THE UNIVERSAL FEATURES OF CELLS ON EARTH

All Cells Translate RNA into Protein in the Same Way

THE UNIVERSAL FEATURES OF CELLS ON EARTH

Each Protein Is Encoded by a Specific Gene

THE UNIVERSAL FEATURES OF CELLS ON EARTH

Life Requires Free Energy

THE UNIVERSAL FEATURES OF CELLS ON EARTH

All Cells Function as Biochemical Factories Dealing with the Same Basic Molecular Building Blocks

THE UNIVERSAL FEATURES OF CELLS ON EARTH

All Cells Are Enclosed in a Plasma Membrane Across Which Nutrients and Waste Materials Must Pass

All Cells Are Enclosed in a Plasma Membrane Across Which Nutrients and Waste Materials Must Pass

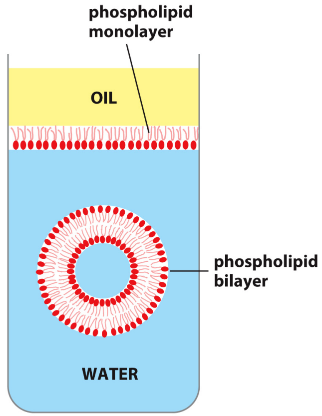


Figure 1–9 Formation of a membrane by amphiphilic phospholipid molecules. Phospholipids have a hydrophilic (water-loving, phosphate) head group and a hydrophobic (water-avoiding, hydrocarbon) tail. At an interface between oil and water, they arrange themselves as a single sheet with their head groups facing the water and their tail groups facing the oil. But when immersed in water, they aggregate to form bilayers enclosing aqueous compartments, as indicated.

THE UNIVERSAL FEATURES OF CELLS ON EARTH

A Living Cell Can Exist with Fewer Than 500 Genes

A Living Cell Can Exist with Fewer Than 500 Genes

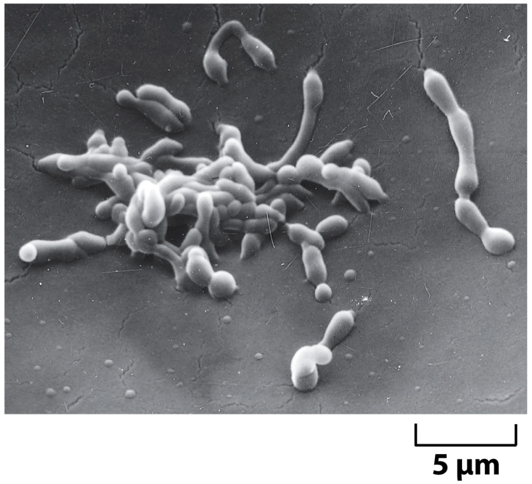
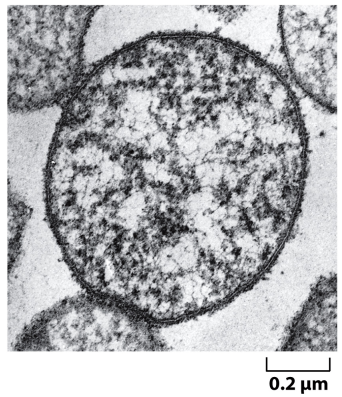


Figure 1–10 Mycoplasma genitalium. (A) Scanning electron micrograph showing the irregular shape of this small bacterium, reflecting the lack of any rigid cell wall.

A Living Cell Can Exist with Fewer Than 500 Genes



(B) Cross section (transmission electron micrograph) of a *Mycoplasma* cell. Of the 530 genes of Mycoplasma genitalium, 43 code for transfer, ribosomal, and other non-messenger RNAs. Functions are known, or can be guessed, for 339 of the genes coding for protein: of these, 154 are involved in eplication, transcription, translation, and related processes involving DNA, RNA, and protein; 98 in the membrane and surface structures of the cell; 46 in the transport of nutrients and other molecules across the membrane; 71 in energy conversion and the synthesis and degradation of small molecules; and 12 in the regulation of cell division and other processes. Note that these categories are partly overlapping, so that some genes feature twice.

Summary

The individual cell is the minimal self-reproducing unit of living matter, and it consists of a self-replicating collection of catalysts. Central to this reproduction is the transmission of genetic information to progeny cells. Every cell on our planet stores its genetic information in the same chemical form—as double-stranded DNA. The cell replicates its information by separating the paired DNA strands and using each as a template for polymerization to make a new DNA strand with a complementary sequence of nucleotides. The same strategy of templated polymerization is used to transcribe portions of the information from DNA into molecules of the closely related polymer, RNA. These RNA molecules in turn guide the synthesis of protein molecules by the more complex machinery of translation, involving a large multi-molecular machine, the ribosome.

Summary

Proteins are the principal catalysts for almost all the chemical reactions in the cell; their other functions include the selective import and export of small molecules across the plasma membrane that forms the cell's boundary. The specific function of each protein depends on its amino acid sequence, which is specified by the nucleotide sequence of a corresponding segment of the DNA—the gene that codes for that protein. In this way, the genome of the cell determines its chemistry; and the chemistry of every living cell is fundamentally similar, because it must provide for the synthesis of DNA, RNA, and protein. The simplest known cells can survive with about 400 genes.

THE DIVERSITY OF GENOMES AND THE TREE OF LIFE

Cells Can Be Powered by a Variety of Free-Energy Source

Cells Can Be Powered by a Variety of Free-Energy Source

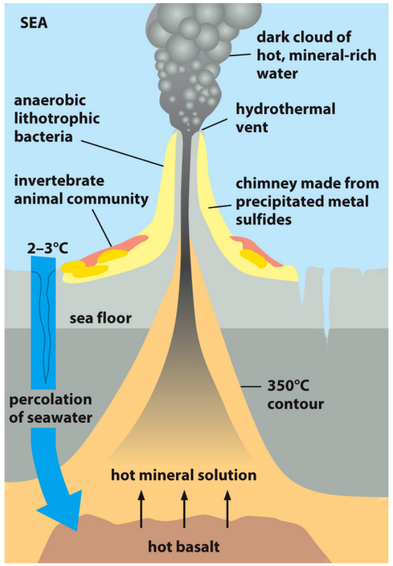


Figure 1-11 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–11 The geology of a hot hydrothermal vent in the ocean floor. As indicated, water percolates down toward the hot molten rock upwelling from the Earth's interior and is heated and driven back upward, carrying minerals leached from the hot rock. A temperature gradient is set up, from more than 350°C near the core of the vent, down to 2–3°C in the surrounding ocean. Minerals precipitate from the water as it cools, forming a chimney. Different classes of organisms, thriving at different temperatures, live in different neighborhoods of the chimney. A typical chimney might be a few meters tall, spewing out hot, mineral-rich water at a flow rate of 1–2 m/sec.

Cells Can Be Powered by a Variety of Free-Energy Source

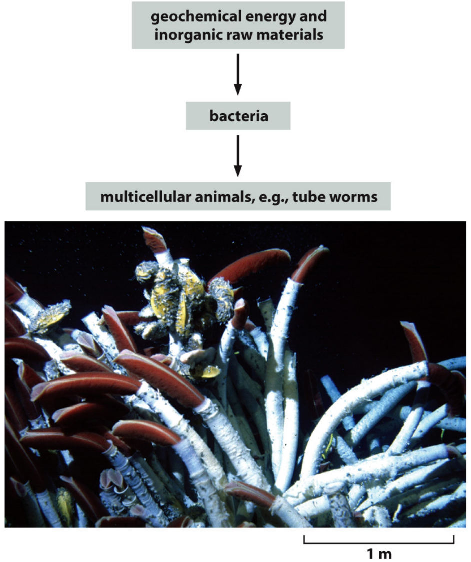


Figure 1-12 Molecular Biology of the Cell 6e (© Garland Science 2015)

Cells Can Be Powered by a Variety of Free-Energy Source

Figure 1–12 Organisms living at adepth of 2500 meters near a vent in the ocean floor. Close to the vent, at temperatures up to about 120°C, various lithotrophic species of bacteria and archaea (archaebacteria) live, directly fueled by geochemical energy. A little further away, where the temperature is lower, various invertebrate animals live by feeding on these microorganisms. Most remarkable are these giant (2 meter) tube worms, *Riftia pachyptila*, which, rather than feed on the lithotrophic cells, live in symbiosis with them: specialized organs in the worms harbor huge numbers of symbiotic sulfur-oxidizing bacteria. These bacteria harness geochemical energy and supply nourishment to their hosts, which have no mouth, gut, or anus. The tube worms are thought to have evolved from more conventional animals, and to have become secondarily adapted to life at hydrothermal vents. (Courtesy of Monika Bright, University of Vienna, Austria.)

THE DIVERSITY OF GENOMES AND THE TREE OF LIFE

Some Cells Fix Nitrogen and Carbon Dioxide for Others

THE DIVERSITY OF GENOMES AND THE TREE OF LIFE

The Greatest Biochemical Diversity Exists Among Prokaryotic Cells

The Greatest Biochemical Diversity Exists Among Prokaryotic Cells

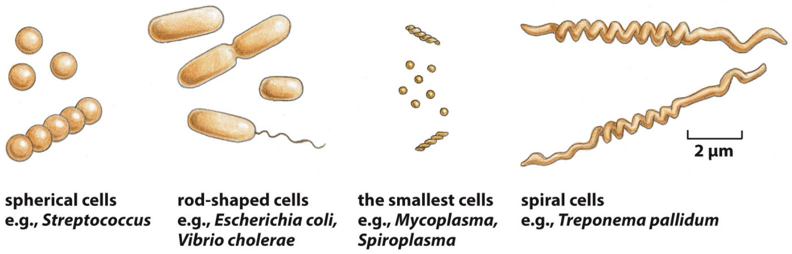


Figure 1-13 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–13 Shapes and sizes of some bacteria. Although most are small, as shown, measuring a few micrometers in linear dimension, there are also some giant species. An extreme example (not shown) is the cigar-shaped bacterium *Epulopiscium fishelsoni*, which lives in the gut of a surgeonfish and can be up to 600 µm long.

The Greatest Biochemical Diversity Exists Among Prokaryotic Cells

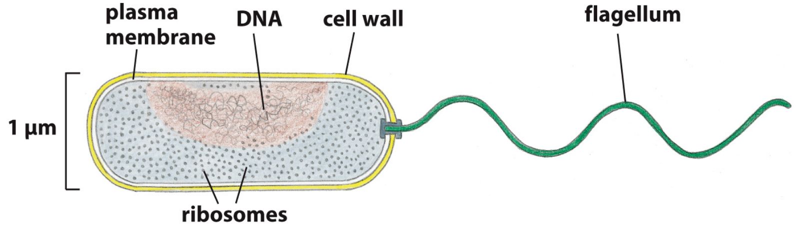


Figure 1-14a Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–14 The structure of a bacterium. (A) The bacterium *Vibrio cholerae*, showing its simple internal organization. Like many other species, *Vibrio* has a helical appendage at one end—a flagellum—that rotates as a propeller to drive the cell forward. It can infect the human small intestine to cause cholera; the severe diarrhea that accompanies this disease kills more than 100,000 people a year.

The Greatest Biochemical Diversity Exists Among Prokaryotic Cells

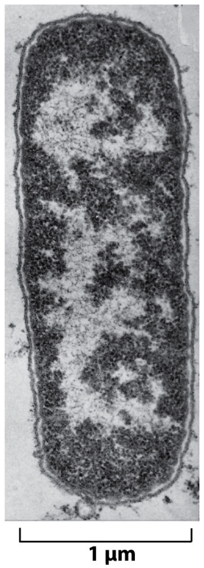


Figure 1-14b Molecular Biology of the Cell 6e (© Garland Science 2015)

(B) An electron micrograph of a longitudinal section through the widely studied bacterium *Escherichia coli (E. coli)*. The cell's DNA is concentrated in the lightly stained region. Part of our normal intestinal flora, *E. coli* is related to *Vibrio*, and it has many flagella distributed over its surface that are not visible in this section. (B, courtesy of E. Kellenberger.)

The Greatest Biochemical Diversity Exists Among Prokaryotic Cells

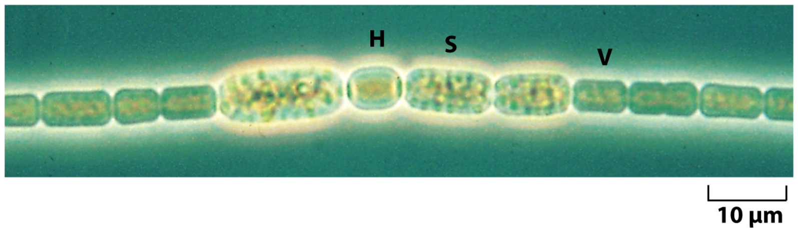


Figure 1-15 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–15 The phototrophic bacterium *Anabaena cylindrica* viewed in the light microscope. The cells of this species form long, multicellular filaments. Most of the cells (labeled V) perform photosynthesis, while others become specialized for nitrogen fixation (labeled H) or develop into resistant spores (labeled S). (Courtesy of Dave G. Adams.)

The Greatest Biochemical Diversity Exists Among Prokaryotic Cells

Figure 1-16 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–16 A lithotrophic bacterium. *Beggiatoa*, which lives in sulfurous environments, gets its energy by oxidizing H2S and can fix carbon even in the dark. Note the yellow deposits of sulfur inside the cells. (Courtesy of Ralph W. Wolfe.)

THE DIVERSITY OF GENOMES AND THE TREE OF LIFE

The Tree of Life Has Three Primary Branches: Bacteria, Archaea, and Eukaryotes

The Tree of Life Has Three Primary Branches: Bacteria, Archaea, and Eukaryotes

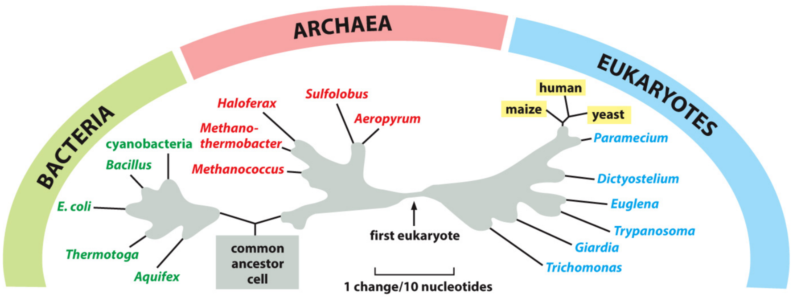


Figure 1-17 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–17 The three major divisions (domains) of the living world. Note that the word *bacteria* was originally used to refer to prokaryotes in general, but more recently has been redefined to refer to eubacteria specifically. The tree shown here is based on comparisons of the nucleotide sequence of a ribosomal RNA (rRNA) subunit in the different species, and the distances in the diagram represent estimates of the numbers of evolutionary changes that have occurred in this molecule in each lineage (see Figure 1–18). The parts of the tree shrouded in *gray cloud* represent uncertainties about details of the true pattern of species divergence in the course of evolution: comparisons of nucleotide or amino acid sequences of molecules other than rRNA, as well as other arguments, can lead to somewhat different trees. As indicated, the nucleus of the eukaryotic cell is now thought to have emerged from a sub-branch within the archaea, so that in the beginning the tree of life had only two branches—bacteria and archaea.

THE DIVERSITY OF GENOMES AND THE TREE OF LIFE

Some Genes Evolve Rapidly; Others Are Highly Conserved

Some Genes Evolve Rapidly; Others Are Highly Conserved

Figure 1-18 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–18 Genetic information conserved since the days of the last common ancestor of all living things. A part of the gene for the smaller of the two main rRNA components of the ribosome is shown. (The complete molecule is about 1500–1900 nucleotides long, depending on species.) Corresponding segments of nucleotide sequence from an archaean *(Methanococcus jannaschii)*, a bacterium *(Escherichia coli)*, and a eukaryote *(Homo sapiens)* are aligned. Sites where the nucleotides are identical between species are indicated by a vertical line; the human sequence is repeated at the bottom of the alignment so that all three two-way comparisons can be seen. A dot halfway along the *E. coli* sequence denotes a site where a nucleotide has been either deleted from the bacterial lineage in the course of evolution or inserted in the other two lineages. Note that the sequences from these three organisms, representative of the three domains of the living world, still retain unmistakable similarities.

THE DIVERSITY OF GENOMES AND THE TREE OF LIFE

Most Bacteria and Archaea Have 1000–6000 Genes

THE DIVERSITY OF GENOMES AND THE TREE OF LIFE

New Genes Are Generated from Preexisting Genes

New Genes Are Generated from Preexisting Genes

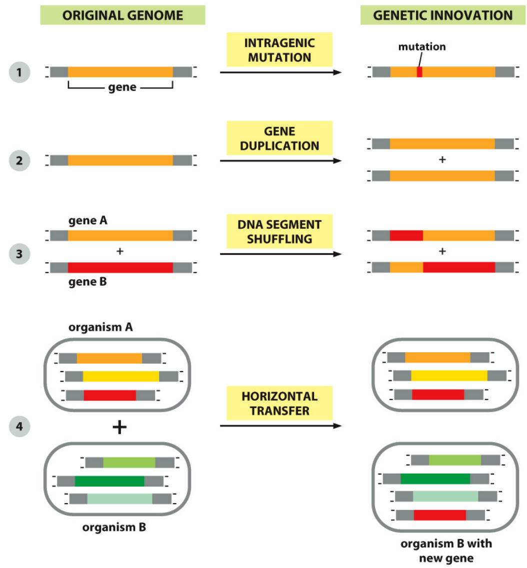


Figure 1-19 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–19 Four modes of genetic innovation and their effects on the DNA sequence of an organism. A special form of horizontal transfer occurs when two different types of cells enter into a permanent symbiotic association. Genes from one of the cells then may be transferred to the genome of the other, as we shall see below when we discuss mitochondria and chloroplasts.

THE DIVERSITY OF GENOMES AND THE TREE OF LIFE

Gene Duplications Give Rise to Families of Related Genes Within a Single Cell

Gene Duplications Give Rise to Families of Related Genes Within a Single Cell

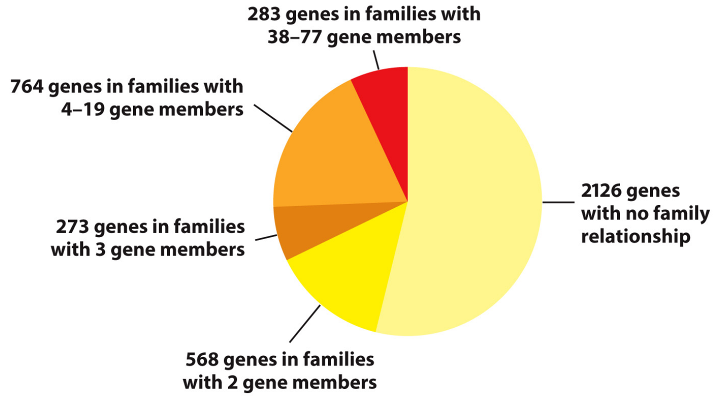


Figure 1-20 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–20 Families of evolutionarily related genes in the genome of *Bacillus subtilis*. The largest gene family in this bacterium consists of 77 genes coding for varieties of ABC transporters—a class of membrane transport proteins found in all three domains of the living world. (Adapted from F. Kunst et al., *Nature* 390:249–256, 1997. With permission from Macmillan Publishers Ltd.)

Gene Duplications Give Rise to Families of Related Genes Within a Single Cell

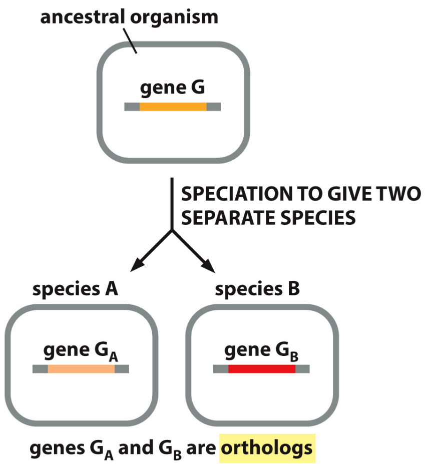


Figure 1-21a Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–21 Paralogous genes and orthologous genes: two types of gene homology based on different evolutionary pathways. (A) Orthologs. (B) Paralogs.

Gene Duplications Give Rise to Families of Related Genes Within a Single Cell

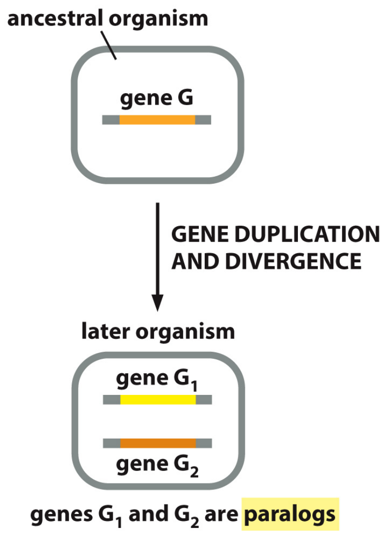


Figure 1-21b Molecular Biology of the Cell 6e (© Garland Science 2015)

THE DIVERSITY OF GENOMES AND THE TREE OF LIFE

Genes Can Be Transferred Between Organisms, Both in the Laboratory and in Nature

Genes Can Be Transferred Between Organisms, Both in the Laboratory and in Nature

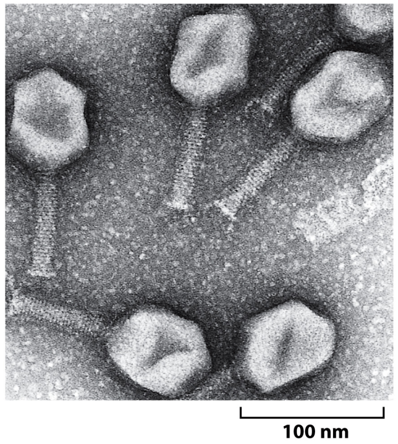


Figure 1-22a Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–22 The viral transfer of DNA into a cell. (A) An electron micrograph of particles of a bacterial virus, the T4 bacteriophage. The head of this virus contains the viral DNA; the tail contains the apparatus for injecting the DNA into a host bacterium.

Genes Can Be Transferred Between Organisms, Both in the Laboratory and in Nature

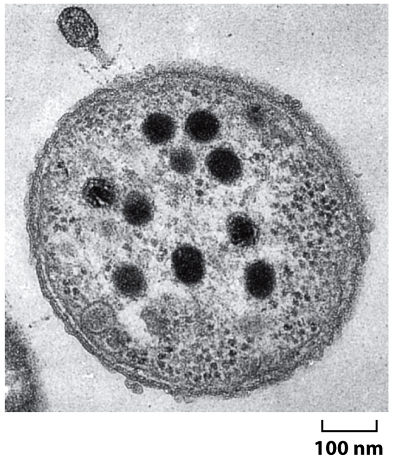


Figure 1-22b Molecular Biology of the Cell 6e (© Garland Science 2015)

(B) A cross section of an *E. coli* bacterium with a T4 bacteriophage latched onto its surface. The large dark objects inside the bacterium are the heads of new T4 particles in the course of assembly. When they are mature, the bacterium will burst open to release them.

Genes Can Be Transferred Between Organisms, Both in the Laboratory and in Nature

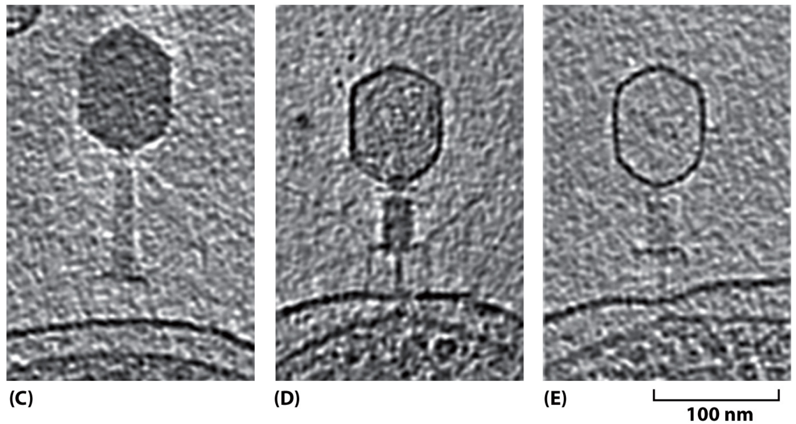


Figure 1-22cde Molecular Biology of the Cell 6e (© Garland Science 2015)

(C–E) The process of DNA injection into the bacterium, as visualized in unstained, frozen samples by cryoelectron microscopy. (C) Attachment begins. (D) Attached state during DNA injection.
(E) Virus head has emptied all of its DNA into the bacterium.

THE DIVERSITY OF GENOMES AND THE TREE OF LIFE

Sex Results in Horizontal Exchanges of Genetic Information Within a Species

THE DIVERSITY OF GENOMES AND THE TREE OF LIFE

The Function of a Gene Can Often Be Deduced from Its Sequence

THE DIVERSITY OF GENOMES AND THE TREE OF LIFE

More Than 200 Gene Families Are Common to All Three Primary Branches of the Tree of Life

More Than 200 Gene Families Are Common to All Three Primary Branches of the Tree of Life

TABLE 1–1 The Number of Gene Families, Classified by Function, Common to All Three Domains of the Living World

Information processing		**Metabolism**	
Translation	63	Energy production and conversion	19
Transcription	7	Carbohydrate transport and metabolism	16
Replication, recombination, and repair	13	Amino acid transport and metabolism	43
Cellular processes and signaling		Nucleotide transport and metabolism	15
Cell-cycle control, mitosis, and meiosis	2	Coenzyme transport and metabolism	22
Defense mechanisms	3	Lipid transport and metabolism	9
Signal transduction mechanisms	1	Inorganic ion transport and metabolism	8
Cell wall/membrane biogenesis	2	Secondary metabolite biosynthesis, transport, and catabolism	5
Intracellular trafficking and secretion	4	**Poorly characterized**	
Post-translational modification, protein turnover, chaperones	8	General biochemical function predicted; specific biological role unknown	24

For the purpose of this analysis, gene families are defined as “universal” if they are represented in the genomes of at least two diverse archaea (*Archaeoglobus fulgidus and Aeropyrum pernix*), two evolutionarily distant bacteria (*Escherichia coli* and *Bacillus subtilis*), and one eukaryote (yeast, *Saccharomyces cerevisiae*). (Data from R.L. Tatusov, E.V. Koonin, and D.J. Lipman, *Science* 278:631–637, 1997. With permission from AAAS; R.L. Tatusov et al., *BMC Bioinformatics* 4:41, 2003. With permission from BioMed Central; and the COGs database at the US National Library of Medicine.)

Table 1-1 Molecular Biology of the Cell 6e (© Garland Science 2015)

THE DIVERSITY OF GENOMES AN THE TREE OF LIFE

Mutations Reveal the Functions of Genes

Mutations Reveal the Functions of Genes

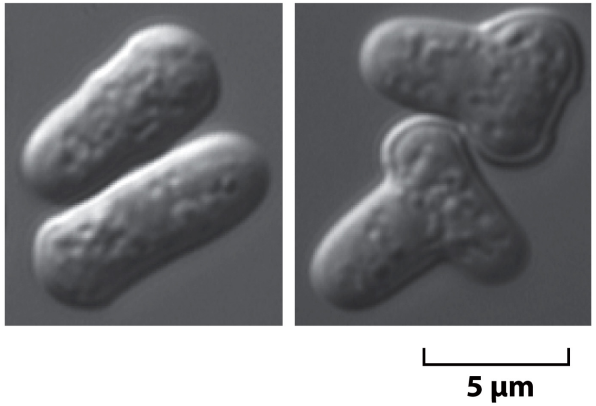


Figure 1-23 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–23 A mutant phenotype reflecting the function of a gene. A normal yeast (of the species *Schizosaccharomyces pombe*) is compared with a mutant in which a change in a single gene has converted the cell from a cigar shape *(left)* to a T shape *(right)*. The mutant gene therefore has a function in the control of cell shape. But how, in molecular terms, does the gene product perform that function? That is a harder question, and it needs biochemical analysis to answer it. (Courtesy of Kenneth Sawin and Paul Nurse.)

THE DIVERSITY OF GENOMES AND THE TREE OF LIFE

Molecular Biology Began with a Spotlight on *E. coli*

Molecular Biology Began with a Spotlight on *E. coli*

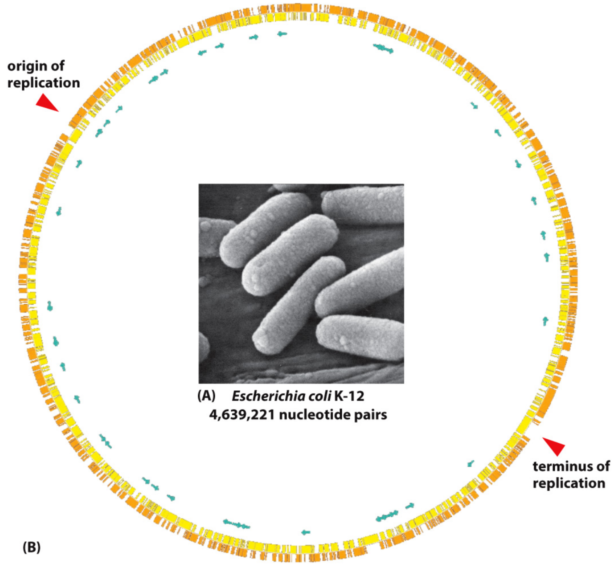


Figure 1-24 Molecular Biology of the Cell 6e (© Garland Science 2015)

Molecular Biology Began with a Spotlight on *E. coli*

Figure 1–24 The genome of *E. coli*. (A) A cluster of *E. coli* cells. (B) A diagram of the genome of *E. coli* strain K-12. The diagram is circular because the DNA of *E. coli*, like that of other prokaryotes, forms a single, closed loop. Protein-coding genes are shown as *yellow* or *orange bars*, depending on the DNA strand from which they are transcribed; genes encoding only RNA molecules are indicated by *green arrows*. Some genes are transcribed from one strand of the DNA double helix (in a clockwise direction in this diagram), others from the other strand (counterclockwise). (A, courtesy of Dr. Tony Brain and David Parker/Photo Researchers; B, adapted from F.R. Blattner et al., *Science* 277:1453–1462, 1997.)

Summary

Prokaryotes (cells without a distinct nucleus) are biochemically the most diverse organisms and include species that can obtain all their energy and nutrients from inorganic chemical sources, such as the reactive mixtures of minerals released at hydrothermal vents on the ocean floor—the sort of diet that may have nourished the first living cells 3.5 billion years ago. DNA sequence comparisons reveal the family relationships of living organisms and show that the prokaryotes fall into two groups that diverged early in the course of evolution: the bacteria (or eubacteria) and the archaea. Together with the eukaryotes (cells with a membrane-enclosed nucleus), these constitute the three primary branches of the tree of life.

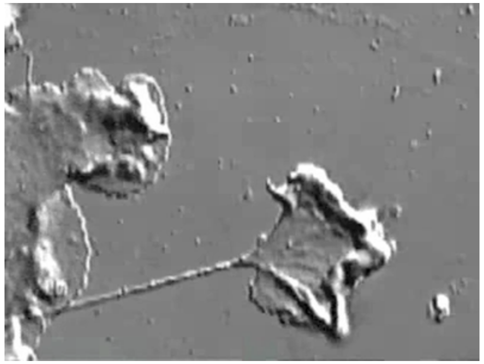
Summary

Most bacteria and archaea are small unicellular organisms with compact genomes comprising 1000–6000 genes. Many of the genes within a single organism show strong family resemblances in their DNA sequences, implying that they originated from the same ancestral gene through gene duplication and divergence. Family resemblances (homologies) are also clear when gene sequences are compared between different species, and more than 200 gene families have been so highly conserved that they can be recognized as common to most species from all three domains of the living world. Thus, given the DNA sequence of a newly discovered gene, it is often possible to deduce the gene's function from the known function of a homologous gene in an intensively studied model organism, such as the bacterium E. coli.

GENETIC INFORMATION IN EUKARYOTES

Eukaryotic Cells May Have Originated as Predators

Eukaryotic Cells May Have Originated as Predators



01.1_Keratocyte_Dance

Eukaryotic Cells May Have Originated as Predators

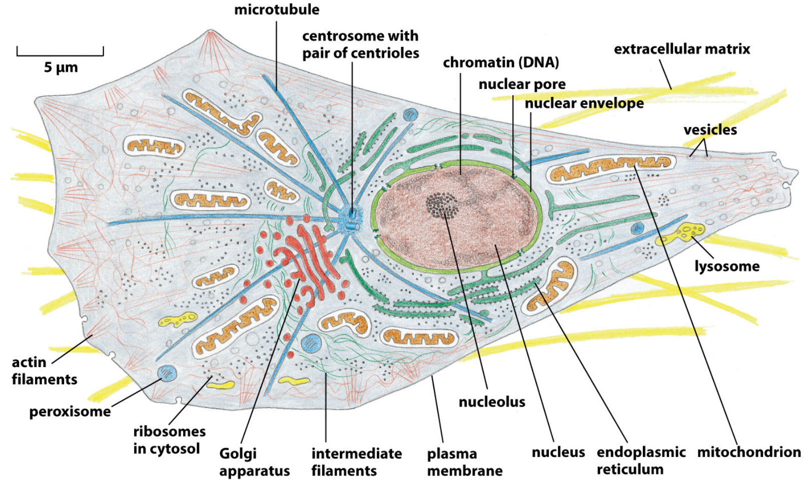


Figure 1-25 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–25 The major features of eukaryotic cells. The drawing depicts a typical animal cell, but almost all the same components are found in plants and fungi as well as in single-celled eukaryotes such as yeasts and protozoa. Plant cells contain chloroplasts in addition to the components shown here, and their plasma membrane is surrounded by a tough external wall formed of cellulose.

Eukaryotic Cells May Have Originated as Predators

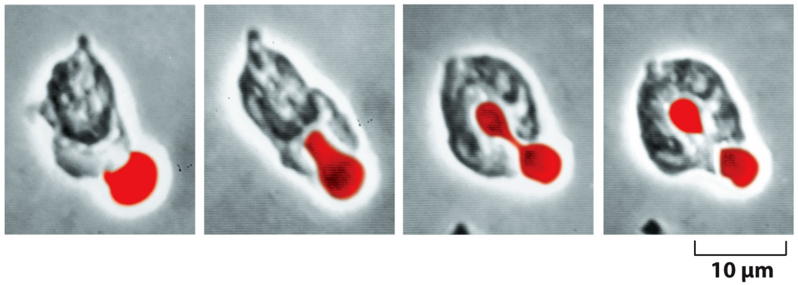


Figure 1-26 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–26 Phagocytosis. This series of stills from a movie shows a human white blood cell (a neutrophil) engulfing a red blood cell (artificially colored *red)* that has been treated with an antibody that marks it for destruction (see Movie 13.5). (Courtesy of Stephen E. Malawista and Anne de Boisfleury Chevance.)

Eukaryotic Cells May Have Originated as Predators

Figure 1-27a Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–27 A single-celled eukaryote that eats other cells. (A) *Didinium* is a carnivorous protozoan, belonging to the group known as *ciliates*. It has a globular body, about 150 µm in diameter, encircled by two fringes of cilia—sinuous, whiplike appendages that beat continually; its front end is flattened except for a single protrusion, rather like a snout.

Eukaryotic Cells May Have Originated as Predators

Figure 1-27b Molecular Biology of the Cell 6e (© Garland Science 2015)

(B) A *Didinium* engulfing its prey. *Didinium* normally swims around in the water at high speed by means of the synchronous beating of its cilia. When it encounters a suitable prey *(yellow)*, usually another type of protozoan, it releases numerous small paralyzing darts from its snout region. Then, the *Didinium* attaches to and devours the other cell by phagocytosis, inverting like a hollow ball to engulf its victim, which can be almost as large as itself. (Courtesy of D. Barlow.)

GENETIC INFORMATION IN EUKARYOTES

Modern Eukaryotic Cells Evolved from a Symbiosis

Modern Eukaryotic Cells Evolved from a Symbiosis

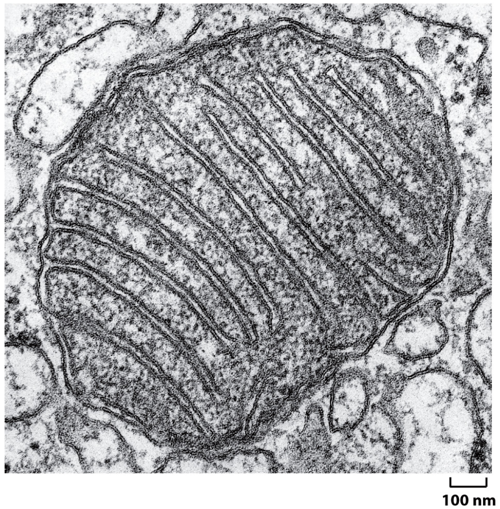


Figure 1-28a Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–28 A mitochondrion. (A) A cross section, as seen in the electron microscope.

Modern Eukaryotic Cells Evolved from a Symbiosis

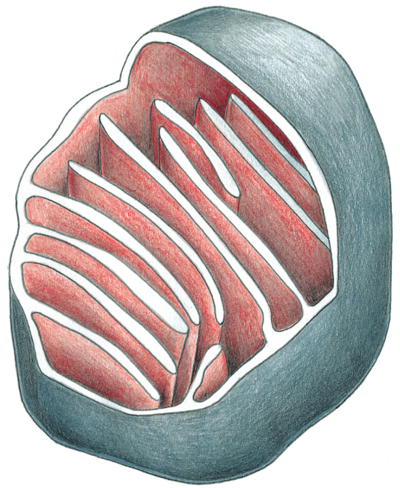
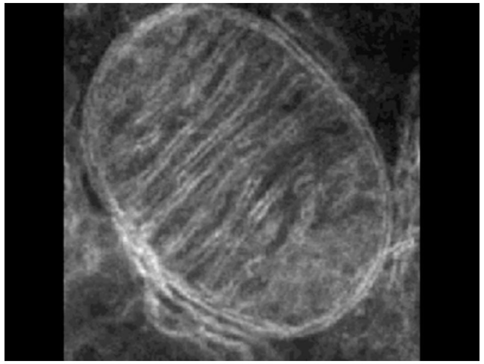


Figure 1-28b Molecular Biology of the Cell 6e (© Garland Science 2015)

(B) A drawing of a mitochondrion with part of it cut away to show the three- dimensional structure (Movie 1.2).

Modern Eukaryotic Cells Evolved from a Symbiosis



01.2_Mito_Tomography_I

Modern Eukaryotic Cells Evolved from a Symbiosis

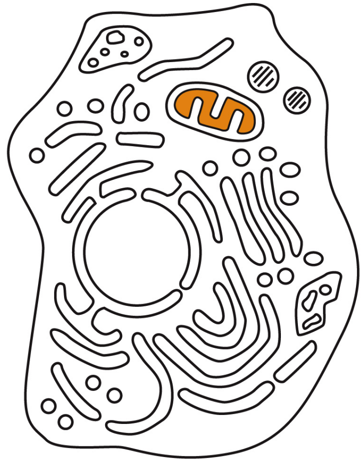


Figure 1-28c Molecular Biology of the Cell 6e (© Garland Science 2015)

(C) A schematic eukaryotic cell, with the interior space of a mitochondrion, containing the mitochondrial DNA and ribosomes, colored. Note the smooth outer membrane and the convoluted inner membrane, which houses the proteins that generate ATP from the oxidation of food molecules. (A, courtesy of Daniel S. Friend.)

Modern Eukaryotic Cells Evolved from a Symbiosis

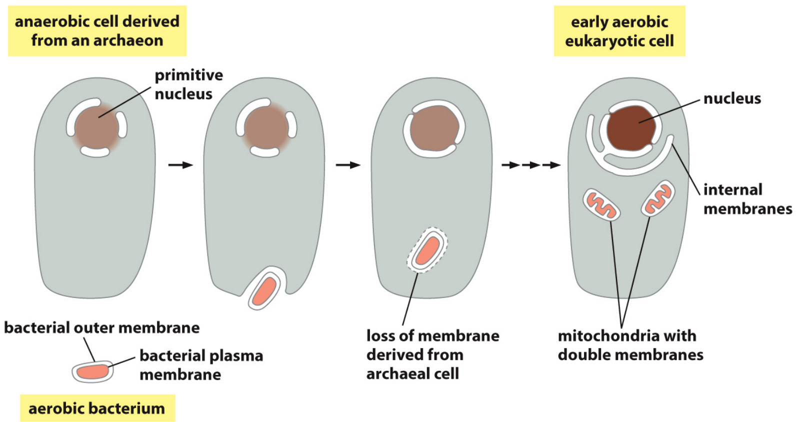


Figure 1-29 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–29 The origin of mitochondria. An ancestral anaerobic predator cell (an archaeon) is thought to have engulfed the bacterial ancestor of mitochondria, initiating a symbiotic relationship. Clear evidence of a dual bacterial and archaeal inheritance can be discerned today in the genomes of all eukaryotes.

Modern Eukaryotic Cells Evolved from a Symbiosis

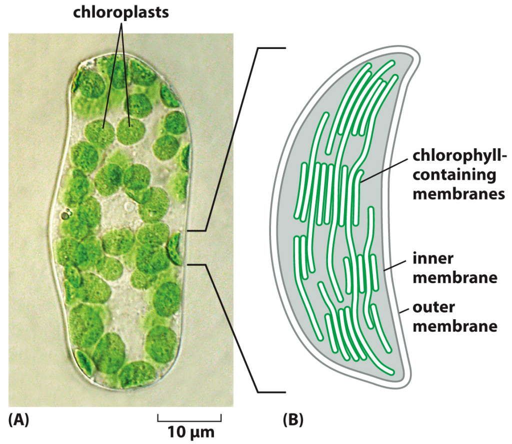
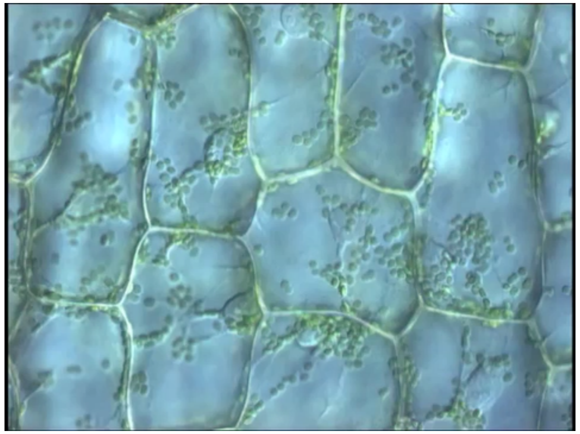


Figure 1-30 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–30 Chloroplasts. These organelles capture the energy of sunlight in plant cells and some single-celled eukaryotes. (A) A single cell isolated from a leaf of a flowering plant, seen in the light microscope, showing the green chloroplasts (Movie 1.3 and see Movie 14.9). (B) A drawing of one of the chloroplasts, showing the highly folded system of internal membranes containing the chlorophyll molecules by which light is absorbed. (A, courtesy of Preeti Dahiya.)

Modern Eukaryotic Cells Evolved from a Symbiosis



01.3_Cytoplasmic_Streaming

Modern Eukaryotic Cells Evolved from a Symbiosis

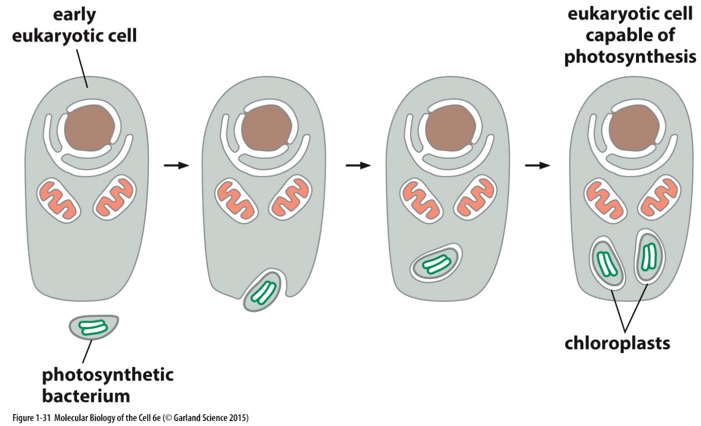


Figure 1–31 The origin of chloroplasts. An early eukaryotic cell, already possessing mitochondria, engulfed a photosynthetic bacterium (a cyanobacterium) and retained it in symbiosis. Present-day chloroplasts are thought to trace their ancestry back to a single species of cyanobacterium that was adopted as an internal symbiont (an endosymbiont) over a billion years ago.

GENETIC INFORMATION IN EUKARYOTES

Eukaryotes Have Hybrid Genomes

GENETIC INFORMATION IN EUKARYOTES

Eukaryotic Genomes Are Big

Eukaryotic Genomes Are Big

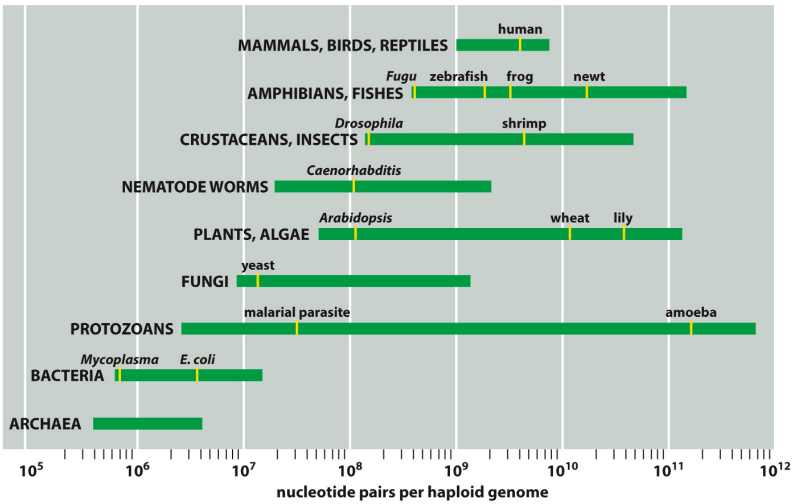


Figure 1-32 Molecular Biology of the Cell 6e (© Garland Science 2015)

Eukaryotic Genomes Are Big

Figure 1–32 Genome sizes compared. Genome size is measured in nucleotide pairs of DNA per haploid genome, that is, per single copy of the genome. (The cells of sexually reproducing organisms such as ourselves are generally diploid: they contain two copies of the genome, one inherited from the mother, the other from the father.) Closely related organisms can vary widely in the quantity of DNA in their genomes, even though they contain similar numbers of functionally distinct genes. (Data from W.H. Li, Molecular Evolution, pp. 380–383. Sunderland, MA: Sinauer, 1997.)

Eukaryotic Genomes Are Big

TABLE 1–2 Some Model Organisms and Their Genomes

Organism	Genome size* (nucleotide pairs)	Approximate number of genes
Escherichia coli (bacterium)	4.6×10^6	4300
Saccharomyces cerevisiae (yeast)	13×10^6	6600
Caenorhabditis elegans (roundworm)	130×10^6	21,000
Arabidopsis thaliana (plant)	220×10^6	29,000
Drosophila melanogaster (fruit fly)	200×10^6	15,000
Danio rerio (zebrafish)	1400×10^6	32,000
Mus musculus (mouse)	2800×10^6	30,000
Homo sapiens (human)	3200×10^6	30,000

*Genome size includes an estimate for the amount of highly repeated DNA sequence not in genome databases.

Table 1-2 Molecular Biology of the Cell 6e (© Garland Science 2015)

GENETIC INFORMATION IN EUKARYOTES

Eukaryotic Genomes Are Rich in Regulatory DNA

GENETIC INFORMATION IN EUKARYOTES

The Genome Defines the Program of Multicellular Development

The Genome Defines the Program of Multicellular Development

Figure 1-33 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–33 Cell types can vary enormously in size and shape. An animal nerve cell is compared here with a neutrophil, a type of white blood cell. Both are drawn to scale.

The Genome Defines the Program of Multicellular Development

Figure 1-34 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–34 Genetic control of the program of multicellular development. The role of a regulatory gene is demonstrated in the snapdragon *Antirrhinum*. In this example, a mutation in a single gene coding for a regulatory protein causes leafy shoots to develop in place of flowers: because a regulatory protein has been changed, the cells adopt characters that would be appropriate to a different location in the normal plant. The mutant is on the left, the normal plant on the right. (Courtesy of Enrico Coen and Rosemary Carpenter.)

GENETIC INFORMATION IN EUKARYOTES

Many Eukaryotes Live as Solitary Cells

Many Eukaryotes Live as Solitary Cells

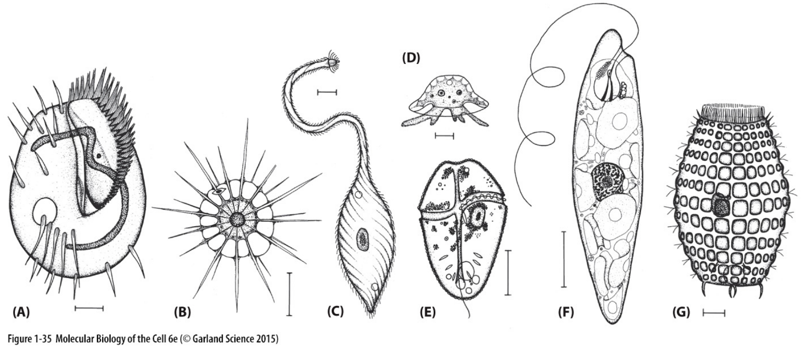
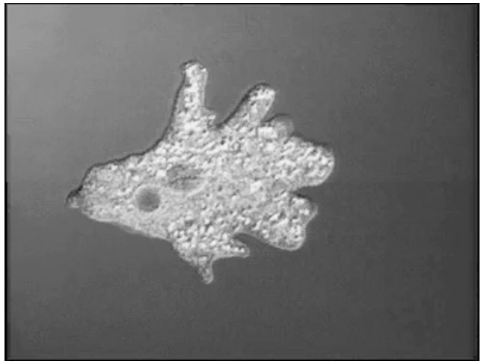


Figure 1–35 An assortment of protozoa: a small sample of an extremely diverse class of organisms. The drawings are done to different scales, but in each case the scale bar represents 10 μm. The organisms in (A), (C), and (G) are ciliates; (B) is a heliozoan; (D) is an amoeba; (E) is a dinoflagellate; and (F) is a euglenoid. (From M.A. Sleigh, Biology of Protozoa. Cambridge, UK: Cambridge University Press, 1973.)

Many Eukaryotes Live as Solitary Cells



01.4_Crawling_Amoeba

Many Eukaryotes Live as Solitary Cells

01.5_Swimming_Eutreptiella

GENETIC INFORMATION IN EUKARYOTES

A Yeast Serves as a Minimal Model Eukaryote

A Yeast Serves as a Minimal Model Eukaryote

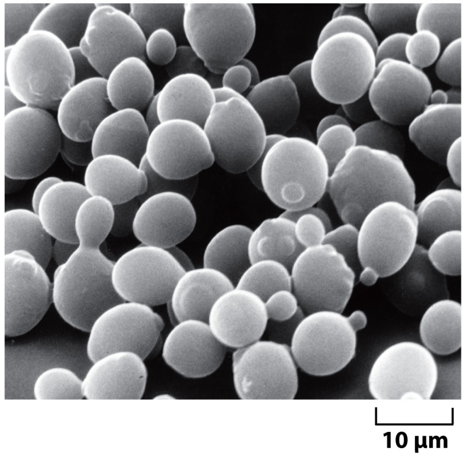


Figure 1-36a Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–36 The yeast *Saccharomyces cerevisiae*. (A) A scanning electron micrograph of a cluster of the cells. This species is also known as budding yeast; it proliferates by forming a protrusion or bud that enlarges and then separates from the rest of the original cell. Many cells with buds are visible in this micrograph.

A Yeast Serves as a Minimal Model Eukaryote

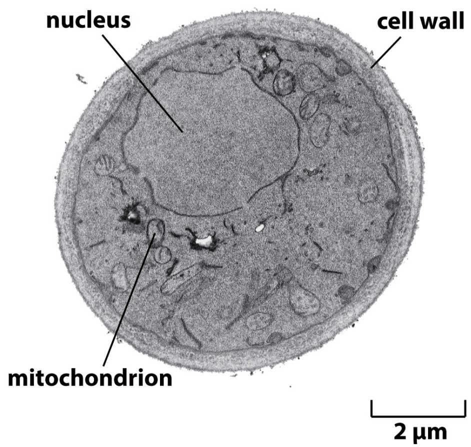


Figure 1-36b Molecular Biology of the Cell 6e (© Garland Science 2015)

(B) A transmission electron micrograph of a cross section of a yeast cell, showing its nucleus, mitochondrion, and thick cell wall. (A, courtesy of Ira Herskowitz and Eric Schabatach.)

A Yeast Serves as a Minimal Model Eukaryote

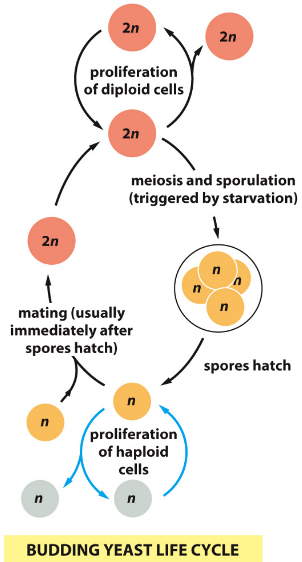


Figure 1-37 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–37 The reproductive cycles of the yeast *S. cerevisiae*. Depending on environmental conditions and on details of the genotype, cells of this species can exist in either a diploid ($2n$) state, with a double chromosome set, or a haploid (n) state, with a single chromosome set. The diploid form can either proliferate by ordinary cell-division cycles or undergo meiosis to produce haploid cells. The haploid form can either proliferate by ordinary cell-division cycles or undergo sexual fusion with another haploid cell to become diploid. Meiosis is triggered by starvation and gives rise to spores—haploid cells in a dormant state, resistant to harsh environmental conditions.

GENETIC INFORMATION IN EUKARYOTES

The Expression Levels of All the Genes of An Organism Can Be Monitored Simultaneously

GENETIC INFORMATION IN EUKARYOTES

Arabidopsis Has Been Chosen Out of 300,000 Species As a Model Plant

Arabidopsis Has Been Chosen Out of 300,000 Species As a Model Plant

Figure 1-38 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–38 *Arabidopsis thaliana*, the plant chosen as the primary model for studying plant molecular genetics. (Courtesy of Toni Hayden and the John Innes Foundation)

GENETIC INFORMATION IN EUKARYOTES

The World of Animal Cells Is Represented By a Worm, a Fly, a Fish, a Mouse, and a Human

The World of Animal Cells Is Represented By a Worm, a Fly, a Fish, a Mouse, and a Human

Figure 1-39 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–39 *Caenorhabditis elegans*, the first multicellular organism to have its complete genome sequence determined. This small nematode, about 1 mm long, lives in the soil. Most individuals are hermaphrodites, producing both eggs and sperm. (Courtesy of Maria Gallegos, University of Wisconsin, Madison.)

GENETIC INFORMATION IN EUKARYOTES

Studies in *Drosophila* Provide a Key to Vertebrate Development

Studies in *Drosophila* Provide a Key to Vertebrate Development

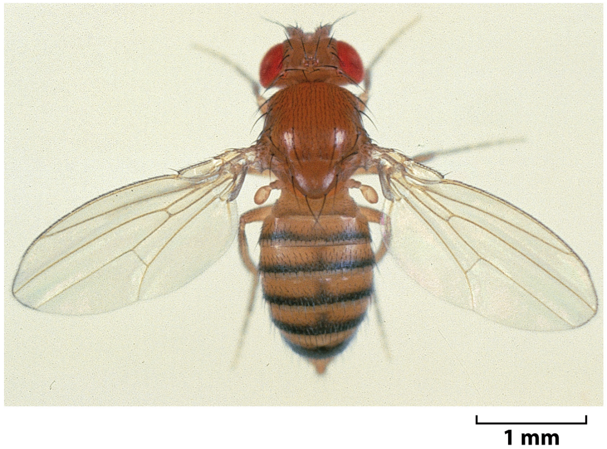


Figure 1-40 Molecular Biology of the Cell 6e (© Garland Science 2015)

igure 1–40 *Drosophila melanogaster.* Molecular genetic studies on this fly have provided the main key to understanding how all animals develop from a fertilized egg into an adult. (From E.B. Lewis, *Science* 221:cover, 1983. With permission from AAAS.)

Studies in *Drosophila* Provide a Key to Vertebrate Development

Figure 1-41 Molecular Biology of the Cell 6e (© Garland Science 2015)

Studies in *Drosophila* Provide a Key to Vertebrate Development

Figure 1–41 Giant chromosomes from salivary gland cells of *Drosophila*. Because many rounds of DNA replication have occurred without an intervening cell division, each of the chromosomes in these unusual cells contains over 1000 identical DNA molecules, all aligned in register. This makes them easy to see in the light microscope, where they display a characteristic and reproducible banding pattern. Specific bands can be identified as the locations of specific genes: a mutant fly with a region of the banding pattern missing shows a phenotype reflecting loss of the genes in that region. Genes that are being transcribed at a high rate correspond to bands with a “puffed” appearance.The bands stained *dark brown* in the micrograph are sites where a particular regulatory protein is bound to the DNA. (Courtesy of B. Zink and R. Paro, from R. Paro, *Trends Genet*. 6:416–421, 1990. With permission from Elsevier.)

GENETIC INFORMATION IN EUKARYOTES

The Vertebrate Genome Is a Product of Repeated Duplications

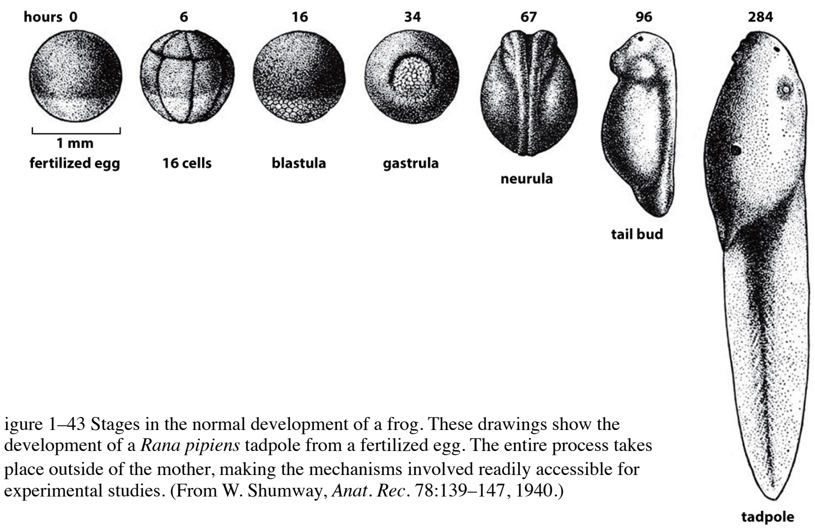
The Vertebrate Genome Is a Product of Repeated Duplications

Figure 1–42 Two species of the frog genus *Xenopus*. *X. tropicalis*, above, has an ordinary diploid genome; *X. laevis*, below, has twice as much DNA per cell. From the banding patterns of their chromosomes and the arrangement of genes along them, as well as from comparisons of gene sequences, it is clear that the large-genome species have evolved through duplications of the whole genome. These duplications are thought to have occurred in the aftermath of matings between frogs of slightly divergent *Xenopus* species. (Courtesy of E. Amaya, M. Offield, and R. Grainger, *Trends Genet*. 14:253– 255, 1998. With permission from Elsevier.)

GENETIC INFORMATION IN EUKARYOTES

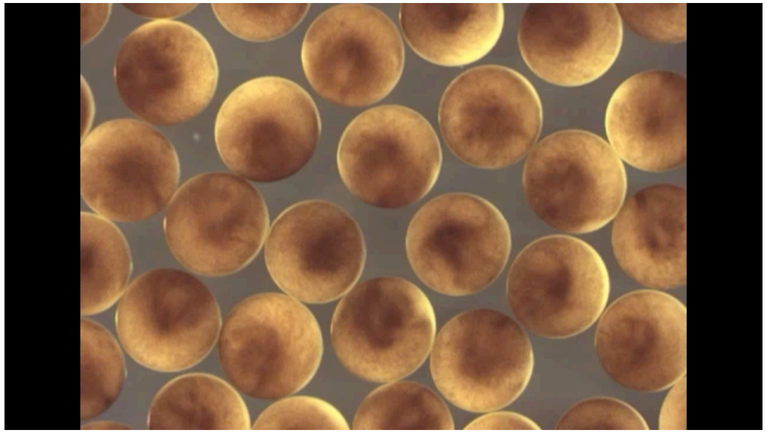
The Frog and the Zebrafish Provide Accessible Models for Vertebrate Development

The Frog and the Zebrafish Provide Accessible Models for Vertebrate Development



igure 1–43 Stages in the normal development of a frog. These drawings show the development of a *Rana pipiens* tadpole from a fertilized egg. The entire process takes place outside of the mother, making the mechanisms involved readily accessible for experimental studies. (From W. Shumway, *Anat. Rec*. 78:139–147, 1940.)

The Frog and the Zebrafish Provide Accessible Models for Vertebrate Development



01.6_Embryonic_Cell_Division

The Frog and the Zebrafish Provide Accessible Models for Vertebrate Development

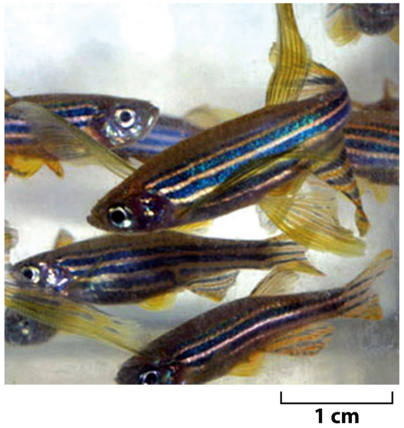


Figure 1-44a Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–44 Zebrafish as a model for studies of vertebrate development. These small, hardy tropical fish are convenient for genetic studies. Additionally, they have transparent embryos that develop outside of the mother, so that one can clearly observe cells moving and changing their character in the living organism throughout its development. (A) Adult fish.

The Frog and the Zebrafish Provide Accessible Models for Vertebrate Development

Figure 1-44b Molecular Biology of the Cell 6e (© Garland Science 2015)

(B) An embryo 24 hours after fertilization. (A, with permission from Steve Baskauf; B, from M. Rhinn et al., *Neural Dev.* 4:12, 2009.)

GENETIC INFORMATION IN EUKARYOTES

The Mouse Is the Predominant Mammalian Model Organism

The Mouse Is the Predominant Mammalian Model Organism

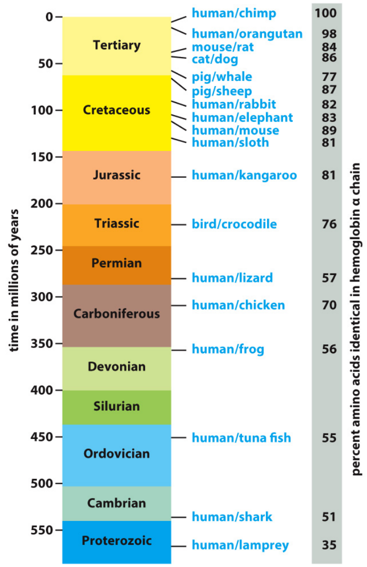


Figure 1-45 Molecular Biology of the Cell 6e (© Garland Science 2015)

The Mouse Is the Predominant Mammalian Model Organism

Figure 1–45 Times of divergence of different vertebrates. The scale on the left shows the estimated date and geological era of the last common ancestor of each specified pair of animals. Each time estimate is based on comparisons of the amino acid sequences of orthologous proteins; the longer the animals of a pair have had to evolve independently, the smaller the percentage of amino acids that remain identical. The time scale has been calibrated to match the fossil evidence showing that the last common ancestor of mammals and birds lived 310 million years ago. The figures on the right give data on sequence divergence for one particular protein—the α chain of hemoglobin. Note that although there is a clear general trend of increasing divergence with increasing time for this protein, there are irregularities that are thought to reflect the action of natural selection driving especially rapid changes of hemoglobin sequence when the organisms experienced special physiological demands. Some proteins, subject to stricter functional constraints, evolve much more slowly than hemoglobin, others as much as five times faster. All this gives rise to substantial uncertainties in estimates of divergence times, and some experts believe that the major groups of mammals diverged from one another as much as 60 million years more recently than shown here. (Adapted from S. Kumar and S.B. Hedges, *Nature* 392:917–920, 1998. With permission from Macmillan Publishers Ltd.)

The Mouse Is the Predominant Mammalian Model Organism

Figure 1-46 Molecular Biology of the Cell 6e (© Garland Science 2015)

Figure 1–46 Human and mouse: similar genes and similar development. The human baby and the mouse shown here have similar white patches on their foreheads because both have mutations in the same gene (called *Kit*), required for the development and maintenance of pigment cells. (Courtesy of R.A. Fleischman.)

GENETIC INFORMATION IN EUKARYOTES

Humans Report on Their Own Peculiarities

GENETIC INFORMATION IN EUKARYOTES

We Are All Different in Detail

GENETIC INFORMATION IN EUKARYOTES

To Understand Cells and Organisms Will Require Mathematics, Computers, and Quantitative Information

To Understand Cells and Organisms Will Require Mathematics, Computers, and Quantitative Information

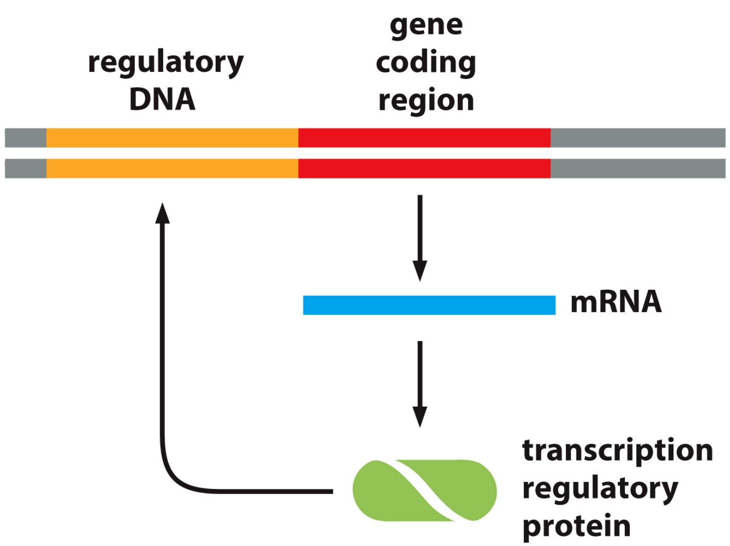


Figure 1-47 Molecular Biology of the Cell 6e (© Garland Science 2015)

To Understand Cells and Organisms Will Require Mathematics, Computers, and Quantitative Information

Figure 1–47 A very simple regulatory circuit—a single gene regulating its own expression by the binding of its protein product to its own regulatory DNA. Simple schematic diagrams such as this are found throughout this book. They are often used to summarize what we know, but they leave many questions unanswered. When the protein binds, does it inhibit or stimulate transcription from the gene? How steeply does the transcription rate depend on the protein concentration? How long, on average, does a molecule of the protein remain bound to the DNA? How long does it take to make each molecule of mRNA or protein, and how quickly does each type of molecule get degraded? As explained in Chapter 8, mathematical modeling shows that we need quantitative answers to all these and other questions before we can predict the behavior of even this single-gene system. For different parameter values, the system may settle to a unique steady state; or it may behave as a switch, capable of existing in one or another of a set of alternative states; or it may oscillate; or it may show large random fluctuations.

Summary

Eukaryotic cells, by definition, keep their DNA in a separate membrane-enclosed compartment, the nucleus. They have, in addition, a cytoskeleton for support and movement, elaborate intracellular compartments for digestion and secretion, the capacity (in many species) to engulf other cells, and a metabolism that depends on the oxidation of organic molecules by mitochondria. These properties suggest that eukaryotes may have originated as predators on other cells. Mitochondria—and, in plants, chloroplasts—contain their own genetic material, and they evidently evolved from bacteria that were taken up into the cytoplasm of ancient cells and survived as symbionts.

Summary

Eukaryotic cells typically have 3–30 times as many genes as prokaryotes, and often thousands of times more noncoding DNA. The noncoding DNA allows for great complexity in the regulation of gene expression, as required for the construction of complex multicellular organisms. Many eukaryotes are, however, unicellular—among them the yeast Saccharomyces cerevisiae, which serves as a simple model organism for eukaryotic cell biology, revealing the molecular basis of many fundamental processes that have been strikingly conserved during a billion years of evolution. A small number of other organisms have also been chosen for intensive study: a worm, a fly, a fish, and the mouse serve as "model organisms" for multicellular animals; and a small milkweed serves as a model for plants.

Summary

Powerful new technologies such as genome sequencing are producing striking advances in our knowledge of human beings, and they are helping to advance our understanding of human health and disease. But living systems are incredibly complex, and mammalian genomes contain multiple closely related homologs of most genes. This genetic redundancy has allowed diversification and specialization of genes for new purposes, but it also makes biological mechanisms harder to decipher. For this reason, simpler model organisms have played a key part in revealing universal genetic mechanisms of animal development, and research using these systems remains critical for driving scientific and medical advances.