4 Functional Anatomy of Prokaryotic and Eukaryotic Cells

COMPARING PROKARYOTIC AND EUKARYOTIC CELLS: AN OVERVIEW

Distinguishing characteristics of **prokaryotic** (*prenucleus*) cells:

1. Genetic material (DNA) is usually one circular chromosome (some bacteria have two chromosomes, and a few have a linearly arranged chromosome) and is not enclosed within a membrane.
2. Lacking other membrane-enclosed organelles.
3. No histone proteins associated with DNA.
4. Cell walls almost always contain peptidoglycan.
5. Usually divide by **binary fission.**

Distinguishing characteristics of **eukaryotic** (*true nucleus*) cells:

1. Nucleus bounded by a membrane.
2. DNA of multiple chromosomes consistently associated with proteins called histones and nonhistones.
3. Possess mitotic apparatus; divide by mitosis.
4. Possess membrane-enclosed organelles such as mitochondria, endoplasmic reticulum, and sometimes chloroplasts.

THE PROKARYOTIC CELL

THE SIZE, SHAPE, AND ARRANGEMENT OF BACTERIAL CELLS

Bacteria range in size from 0.2 to 2.0 μm in diameter and 2 to 8 μm in length. Basic bacterial shapes are the spherical **coccus** (meaning berry), the rod-shaped **bacillus** (meaning little staff), and the **spiral. Diplococci** form pairs; **streptococci** form chains; **tetrads** divide in two planes, forming groups of four; **sarcinae** divide in three regular planes and form cubelike packets; **staphylococci** divide in irregular, random planes and form grapelike clusters. Most bacilli are single rods, but they can appear in pairs—**diplobacilli**—or in chains—**streptobacilli. Coccobacilli** are ovals. **Vibrios**—slightly curved, commalike rods—are also included among spiral bacteria. **Spirilla** have a helical corkscrew shape and are motile by means of flagella. **Spirochetes** are shaped like spirilla but have axial filaments for motility. **Pleomorphic** bacteria have an irregular morphology; if they maintain a single shape, they are **monomorphic.**

STRUCTURES EXTERNAL TO THE CELL WALL

Glycocalyx

The general term for substances surrounding bacterial cells is **glycocalyx,** which is usually a polysaccharide, polypeptide, or both. If organized and tightly attached, it is called a **capsule** (Figure 4.1). If unorganized and loosely attached, the glycocalyx is called a **slime layer.** If made of sugars, it is called an **extracellular polysaccharide.** The glycocalyx aids in attachment to surfaces; capsules contribute to pathogenicity by protecting from phagocytosis, an important part of the body's defenses.

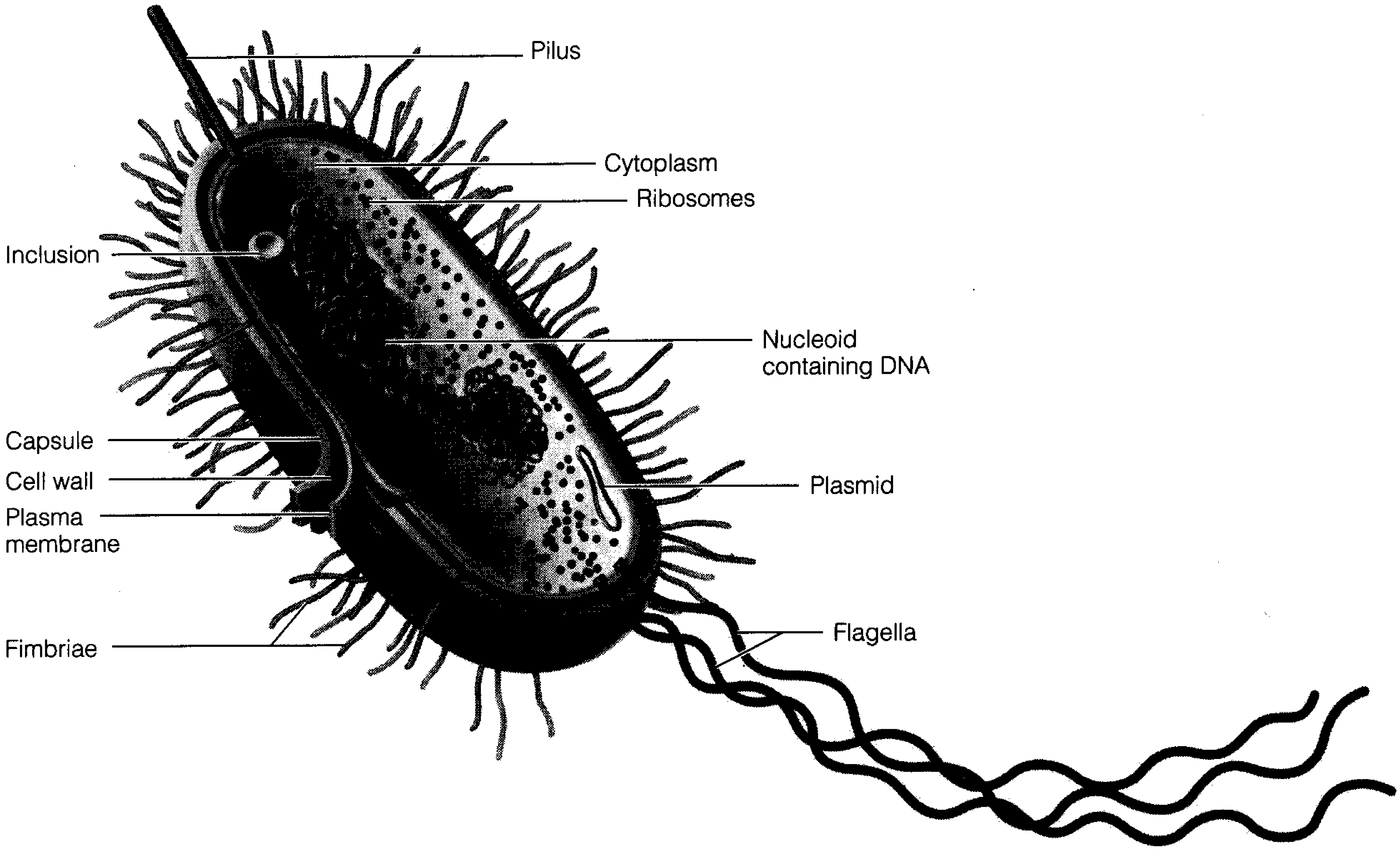


Figure 4.1 Structure of a typical prokaryotic (bacterial) cell. In this diagram, the cell has been sectioned lengthwise to reveal the internal structures.

Flagella

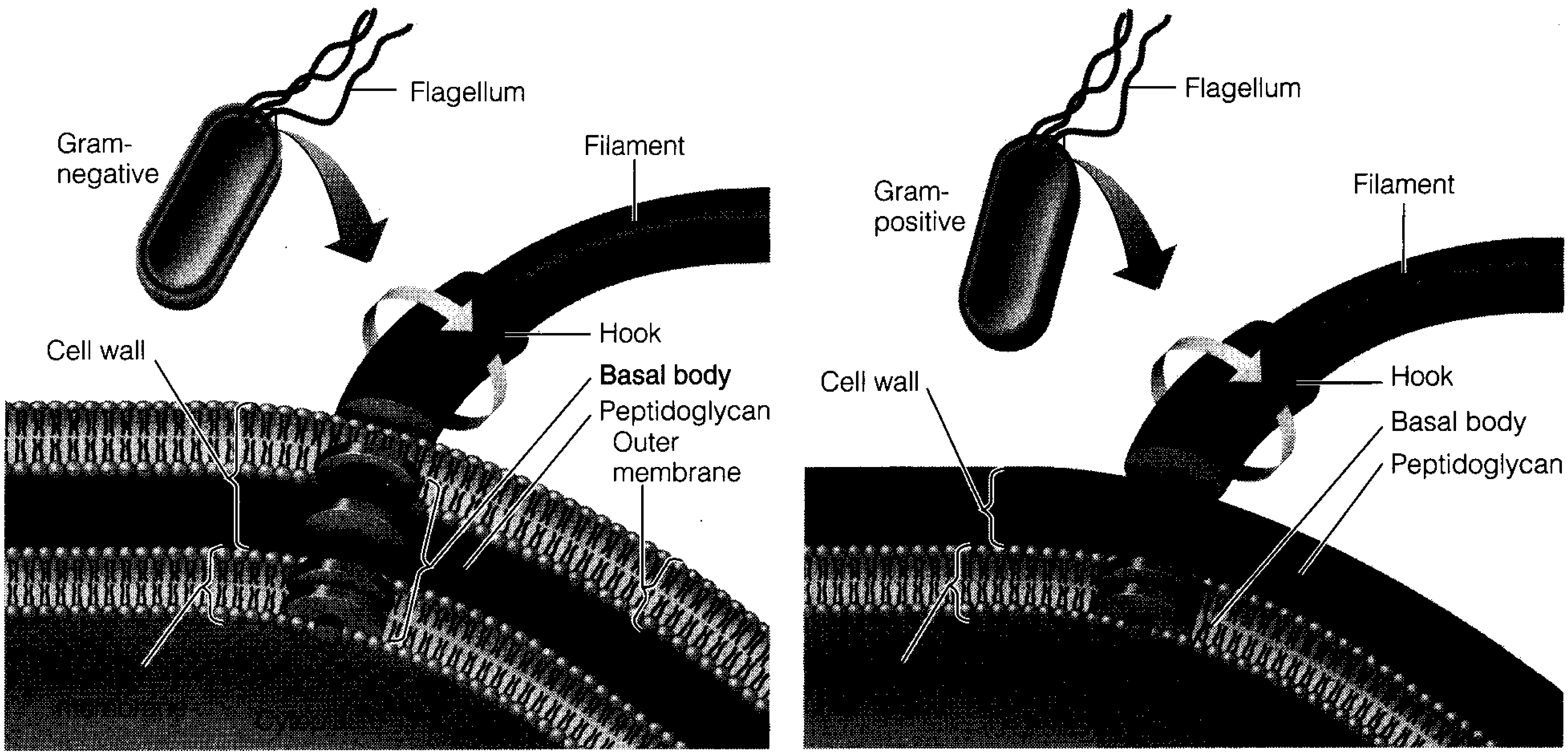
Flagellar filaments are composed of a protein, **flagellin.** The base of the flagellar filament widens to a hook. Attached to the hook is a **basal body** (a rod with rings), which anchors the flagellum to the cell wall and plasma membrane (Figure 4.2). The basal body of gram-negative bacteria is anchored to the cell wall and plasma membrane; in gram-positive bacteria, it is anchored only at the plasma membrane. Flagella, when present, are arranged in certain ways: **peritrichous** (distributed over the entire cell) or **polar** (at one or both poles of cell). Polar flagella may be **monotrichous** (a single flagellum at one pole), **lophotrichous** (a tuft of flagella at one pole), or **amphitrichous** (flagella at both poles). Bacteria with no flagella are **atrichous.** Flagella may spin clockwise or counterclockwise, producing directional movement (a "run" or "swim") or random changes in direction ("tumbles"). Movement to or from a stimulus is called **taxis;** the stimulus may be chemicals **(chemotaxis)** or light **(phototaxis).** A flagellar protein, H antigen, is useful for helping to distinguish **serovars,** or variation within a species.

Axial Filaments

Spirochetes move by means of **axial filaments (endoflagella),** bundles of fibrils that arise near cell poles beneath an outer sheath and wrap in spiral fashion around the cell. These can cause the spirochetes to move in a corkscrew manner.

Fimbriae and Pili

Many bacterial cells have numerous hairlike appendages called **fimbriae** that are shorter than flagella (see Figure 4.11 in the text) and consist of a protein, **pilin.** They help the cell adhere to surfaces such as mucous membranes—often a factor in pathogenicity. **Pili** are longer than fimbriae and number only one or two per cell. These are sometimes called **sex pili** because they can function to transfer DNA from one cell to another, called **conjugation.** (See Figure 8.26 in the text.)



(a) Parts and attachment of a flagellum of a gram-negative bacterium

(b) Parts and attachment of a flagellum of a gram-positive bacterium

Figure 4.2 The structure of a prokaryotic flagellum. The parts and attachment of a flagellum of a gram-negative bacterium and gram-positive bacterium are shown in these highly schematic diagrams.

There are several types of motility. In **twitching motility,** also called the *grappling hook model,* a pilus extends by addition of subunits of pilin and contacts another cell, causing movement by retraction as subunits of pilin are removed). **Gliding motility** is used by myxobacteria; the exact mechanism is unknown.

THE CELL WALL

The bacterial **cell wall** is a semirigid structure giving the characteristic shape of the cell.

Composition and Characteristics

The cell wall of gram-positive bacteria is composed of **peptidoglycan,** which consists of two sugars, N-acetylglucosamine and N-acetylmuramic acid (*murein* from *murus,* meaning wall), and also chains of amino acids. The two sugars alternate with each other, forming a carbohydrate (glycan) backbone. Peptide side chains of four amino acids attached to the N-acetylmuramic acid are cross-linked to form the macromolecule of the cell wall. Many gram-positive bacteria also contain polysaccharides called *teichoic acids.* The cell wall of acid-fast bacteria (otherwise considered gram-positive) consists of peptidoglycan and a waxy lipid, mycolic acid.

The cell wall of gram-negative bacteria also contains peptidoglycans, but only thin layers. These cells have a lipoprotein, lipopolysaccharide (**LPS**), and a phospholipid **outer membrane** surrounding their peptidoglycan layers. A **periplasm** (a fluid-filled space) is found between the outer membrane and the **plasma membrane.** The outer membrane also provides resistance to phagocytosis and the action or complement (also part of host defenses). When the cell disintegrates in the host's bloodstream, the lipid portion of the LPS (**lipid A**) is released as an **endotoxin** that can cause illness. Materials may penetrate the outer membrane through channels called **porins.** The **O polysaccharide** extends outward from the core polysaccharide and is composed of sugar molecules, which function as an antigen useful for identifying certain species of gram-negative bacteria.

Cell Walls and the Gram Stain Mechanism

The primary stain, crystal violet, stains both gram-negative and gram-positive bacteria purple because it enters the cytoplasm of both. Iodine, with crystal violet, forms large crystals that cannot be washed through the peptidoglycan wall of gram-positive cells. Alcohol makes the outer membrane of gram-negative cells permeable and allows the crystal violet-iodine crystals to wash out, making them colorless. Safranin counterstain turns gram-negative cells pink. Archaea appear gram-negative because they do not contain peptidoglycans.

Atypical Cell Walls

Mycoplasma bacteria do not have cell walls. They are unique also in having sterols in their plasma membranes. Archaea do not have peptidoglycan in their walls but have a similar substance, **pseudomurein.** Some bacteria of the genus *Proteus* may spontaneously, or in response to penicillin, lose their cell walls and become **L forms.** Later, they may spontaneously revert to walled bacteria.

Acid-Fast Cell Walls

These bacteria contain high concentrations of a waxy lipid, **mycolic acid,** that prevents Gram staining. They are stained with red carbolfuchsin dye. The heated dye penetrates the cell wall and resists removal with acid-alcohol.

Damage to the Cell Wall

Lysozyme—an enzyme occurring in tears, mucus, and saliva—damages the cell walls of many gram-positive bacteria. A bacterium that has lost its cell wall and is surrounded only by the plasma membrane is a **protoplast.** Gram-negative cells treated with lysozyme retain much of the outer membrane layer and are called **spheroplasts.** Both are sensitive to rupture by **osmotic lysis.**

STRUCTURES INTERNAL TO THE CELL WALL

The Plasma (Cytoplasmic) Membrane

The **plasma (cytoplasmic) membrane** is just internal to the cell wall and encloses the cytoplasm. In prokaryotes it consists primarily of phospholipids and proteins. Eukaryotic plasma membranes also contain sterols, making them more rigid. Both prokaryotic and eukaryotic membranes have a two-layered structure, molecules in parallel rows, called a **phospholipid bilayer.** One end (phosphate) is water-soluble, and the other (hydrocarbon) is insoluble. The water-soluble ends are on the outside of the bilayer. Protein molecules are embedded in the membrane; along with phospholipids, they may move freely within the membrane. This arrangement is called the **fluid mosaic model.**

The most important function of the plasma membrane is as a selective barrier. It is **selectively permeable (semipermeable),** and certain molecules and ions pass through, whereas others do not. Several factors affect permeability. Large molecules such as proteins cannot pass; smaller molecules such as amino acids and simple sugars can pass if uncharged. (The phosphate end of the bilayer is charged.) Lipid-soluble substances, because of the phospholipid content, pass more easily. Plasma membranes contain enzymes that help break down nutrients and produce more energy. The **chromatophores** or **thylakoids,** which contain pigments and enzymes for bacterial photosynthesis, are found in the plasma membranes.

Mesosomes are folds in the plasma membrane that may be only an artifact of preparation for electron microscopy.

Movement of Materials across Membranes

Material crosses plasma membranes by *passive processes* such as **simple diffusion** (movement of molecules or ions from an area of higher concentration to an area of lower concentration). At equilibrium, the concentration gradient has been eliminated. **Osmosis** is the movement of solvent molecules across a selectively permeable membrane. **Osmotic pressure** is the force with which a solvent (such as water) moves from a solution of lower solute concentration (such as dissolved sugar) to a solution of higher solute concentration. **Isotonic (isoosmotic)** solutions have equal solute concentrations on both sides of the membrane. **Hypotonic (hypoosmotic)** solutions have a lower concentration of solutes outside the cell than inside; this is the case with most bacteria. **Hypertonic (hyperosmotic)** solutions have a higher concentration of solutes outside the cell. Bacterial cells placed in such solutions lose water by osmosis and shrink, and the cytoplasm collapses within the cell wall. **Facilitated diffusion,** an *active process,* occurs when a **carrier protein (permease** or **transporter)** combines with and transports a substance across the membrane, but only where a concentration gradient is present. **Active transport** requires cell energy (ATP) and also involves carrier proteins moving substances across the plasma membrane. In **group translocation,** the substance is chemically altered during transport. Once inside, the plasma membrane is impermeable. This is important for low-concentration substances.

Cytoplasm, Nucleoid, Ribosomes, and Inclusions

The term **cytoplasm** refers to everything inside the plasma membrane. It has many **inclusions,** such as **metachromatic granules** of stored phosphate (**volutin**), **polysaccharide granules** of glycogen and starch, **lipid inclusions** such as *poly-beta-hydroxybutyric acid,* and sulfur granules. The cytoplasm also contains many **ribosomes,** the sites of protein synthesis. **Carboxysomes** are inclusions found in bacteria that use carbon dioxide as their sole source of carbon. **Gas vacuoles** or **gas vesicles** help some bacteria maintain buoyancy. The **bacterial chromosome,** which contains the genetic information, is a single, long, circular molecule of DNA found in the **nucleoid.** Small circular DNA molecules, **plasmids,** are not connected to the chromosome and replicate independently. Plasmids do not contain normally essential genes but may provide a selective advantage under abnormal conditions—antibiotic resistance, for example. **Magnetosomes** are inclusions of iron oxide formed by a few gram-negative bacteria that aid the microbe in orienting itself environmentally.

Endospores

Endospores are highly resistant bodies formed by a few bacterial species, such as *Bacillus* and *Clostridium.* **Sporulation** or **sporogenesis** is the process of their formation. First, there is an ingrowth of the plasma membrane (**spore septum**). A small portion of the cytoplasm and newly replicated bacterial chromosome is then surrounded by a membrane, the **forespore.** A thick **spore coat** of protein forms around this membrane. The endospore core is dehydrated and contains considerable *dipicolinic acid,* as well as a few essential materials necessary to return it to its vegetative state, which is accomplished through the process of **germination.**

THE EUKARYOTIC CELL

FLAGELLA AND CILIA

Eukaryotic **flagella** are relatively long; **cilia** are more numerous and are shorter. Both are involved in locomotion, and both contain small tubules of protein called **microtubules.**

THE CELL WALL AND GLYCOCALYX

Most algae and some fungi have **cell walls** containing *cellulose,* and often fungi have *chitin* as well. Yeast cell walls contain the polysaccharides *glucan* and *mannan.* No eukaryotic cell wall contains peptidoglycans. Protozoa have a flexible outer covering called a **pellicle.** In animal cells, the plasma membrane is covered by sticky carbohydrates called the **glycocalyx.**

THE PLASMA (CYTOPLASMIC) MEMBRANE

In eukaryotic cells, the **plasma membrane,** which contains sterols, may be the external cell covering. Substances cross the membrane by mechanisms similar to those in prokaryotes. In addition, a process of engulfment, **endocytosis,** brings particles, even some viruses, into the cell. Examples are **phagocytosis,** used by white blood cells to engulf and destroy bacteria (Chapter 16), and **pinocytosis,** by which liquids and dissolved substances enter cells.

SELF-TESTS

In the matching section, there is only one answer to each question; however, the lettered options (a, b, c, etc.) may be used more than once or not at all.

I. Matching

___ 1. Helical; move by flagella, if present.

___ 2. Spherical; in chains.

___ 3. Divide in three regular planes; spheres form cubelike packets.

___ 4. Helical; axial filaments for motility.

___ 5. A simple, commalike curve.

___ 6. Name means "little staff."

___ 7. Ovals.

a. Sarcinae
b. Tetrads
c. Streptococci
d. Spirochetes
e. Vibrios
f. Bacilli
g. Cocci
h. Spirilla
i. Diplococci
j. Coccobacilli

II. Matching

___ 1. Golgi complex.

___ 2. Meiosis occurs in reproduction.

___ 3. Usually single circular chromosome without histones.

___ 4. Sterols generally present in cell membrane.

___ 5. Cell wall almost always contains peptidoglycans.

___ 6. Nucleus bounded by a membrane.

___ 6. Nucleus bounded by a membrane.

___ 7. DNA contained in a nucleoid.

a. Eukaryotic cell
b. Prokaryotic cell

III. Matching

___ 1. Contain pigments for photosynthesis by bacteria; found in the plasma membrane.

___ 2. Gram-negative bacterial cells after their treatment with lysozyme.

___ 3. Specialized external structures that assist in the transfer of genetic material between cells.

___ 4. Numerous short, hairlike appendages that help in attachment to mucous membranes.

___ 5. General term for substances surrounding bacterial cells.

___ 6. Polysaccharides found in the cell wall of many gram-positive bacteria.

___ 7. Inclusions of iron oxide.

a. Glycocalyx
b. Flagellin
c. Fimbriae
d. Sex pili
e. Capsules
f. Teichoic acids
g. Spheroplasts
h. Protoplasts
i. Chromatophores
j. Chloroplasts
k. Magnetosomes

IV. Matching

___ 1. Metachromatic granules of stored phosphate in prokaryotes.

___ 2. Entrance of fluids and dissolved substances into eukaryotic cells.

___ 3. Membrane-enclosed spheres in phagocytic cells that contain powerful digestive enzymes.

___ 4. The "powerhouses" of the cell.

___ 5. A gel-like fluid found in the eukaryotic nucleus.

___ 6. A folded inner membrane found in mitochondria.

___ 7. Sometimes contributes to movement of a cell.

___ 8. Found in walls of acid-fast bacteria.

a. Volutin
b. Plasmids
c. Cristae
d. Zymogens
e. Ribosomes
f. Nucleoplasm
g. Lysosomes
h. Mitochondria
i. Phagocytosis
j. Pinocytosis
k. Cytoplasmic streaming
l. Mycolic acid

VIII. Matching

___ 1. Extracellular polymeric substances on some bacterial cells; may help cells adhere to surfaces.

___ 2. Bacterial cell with thin peptidoglycan layer, outer membrane of lipopolysaccharide.

___ 3. Protein that forms fimbriae.

___ 4. Bundles of microtubules that probably play a role in cell division of eukaryotic cells.

___ 5. Bacteria that have lost their cell walls and may later spontaneously regain them.

___ 6. Lipid A and O polysaccharide are found on this type of bacteria.

a. Glycocalyx
b. Pilin
c. Gram-positive
d. Gram-negative
e. Centrioles
f. L forms

IX. Matching

___ 1. ER associated with ribosomes.

___ 2. Ingrowth of plasma membrane before endospore formation.

___ 3. Anchors the flagella of bacteria to the cell wall and plasma membrane.

a. Septum
b. Forespore
c. Rough ER
d. Smooth ER
e. Basal body

Fill in the Blanks

1. Chemically, the capsule is a(n) ______________________, a polypeptide, or both.
2. Capsules protect pathogenic bacteria from ______________________, a process by which protective host cells engulf and destroy microorganisms.
3. The Golgi complex consists of flattened sacs called ______________________ that are connected to the endoplasmic reticulum.
4. The ______________________ complex consists of four to eight flattened sacs connected to the endoplasmic reticulum. The function is largely secretion of proteins, lipids, and carbohydrates.
5. The term ______________________ means a lower concentration of solutes outside the cell than inside.

6. Three examples of passive diffusion across membranes are ______________________, ______________________, and ______________________.

7. The protein in the flagellar filaments of bacteria is called ______________________.

8. DNA in eukaryotic cells is combined with protein ______________________ and nonhistones.

Critical Thinking

1. What is a glycocalyx? How is the presence of a glycocalyx related to bacterial virulence?

2. What substances are able to cross the plasma membrane most easily?

3. Describe how a bacterial cell will respond to the following osmotic pressures: isotonic, hypotonic, hypertonic.

4. How is the presence of peptidoglycan in bacterial cells clinically significant?

5. Discuss the endosymbiont hypothesis. Is there any evidence to support the endosymbiont hypothesis?