Chapter 3

Procaryotic Cell Structure and Function

An Overview of Procaryotic Cell Structure

- a wide variety of sizes, shapes, and cellular aggregation patterns
- simpler than eucaryotic cell structure
- unique structures not observed in eucaryotes

Size, Shape, and Arrangement

- **cocci** (s., **coccus**) – spheres
  - diplococci (s., diplococcus) – pairs
  - streptococci – chains
  - staphylococci – grape-like clusters
  - tetrads – 4 cocci in a square
  - sarcinae – cubic configuration of 8 cocci

Size, Shape, and Arrangement

- **bacilli** (s., **bacillus**) – rods
  - coccobacilli – very short rods
  - **vibrios** – curved rods
- **mycelium** – network of long, multinucleate filaments

Size, Shape, and Arrangement

- **spirilla (s., spirillum) – rigid helices**
- **spirochetes – flexible helices**
- **pleomorphic – organisms that are variable in shape**

- largest – ≥50 µm in diameter

- smallest – 0.3 µm in diameter

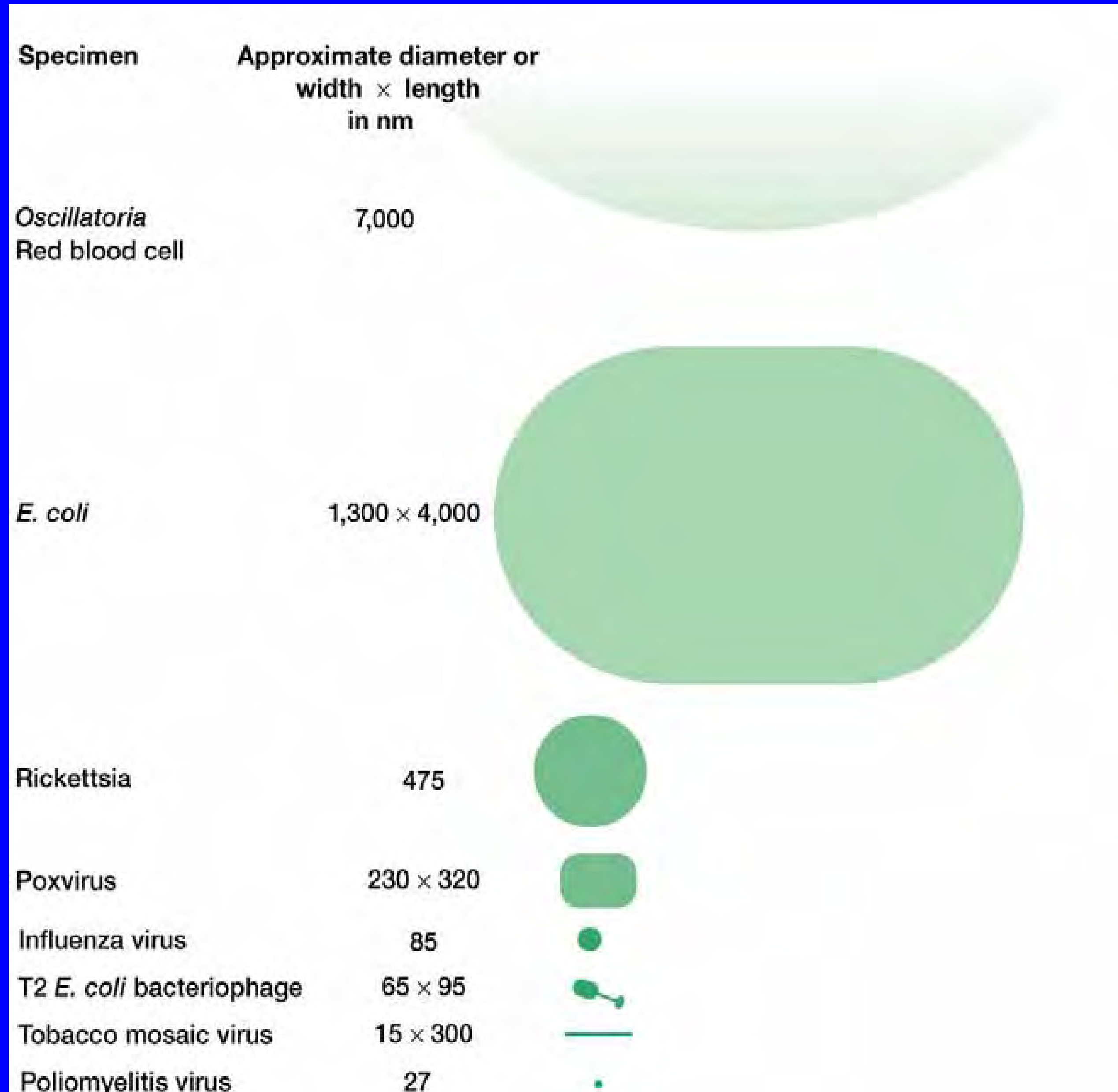
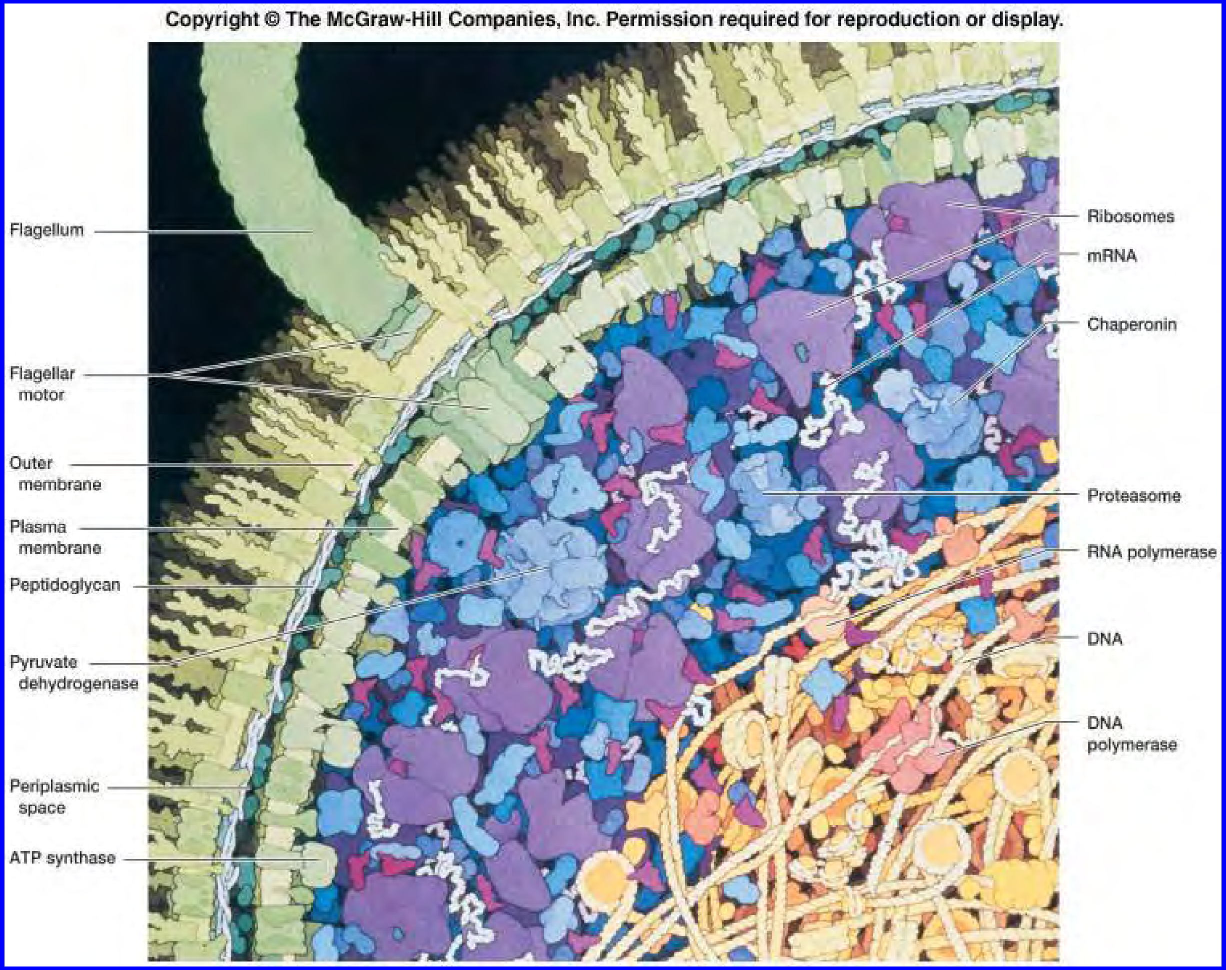


Figure 3.3

Procaryotic Cell Organization



Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

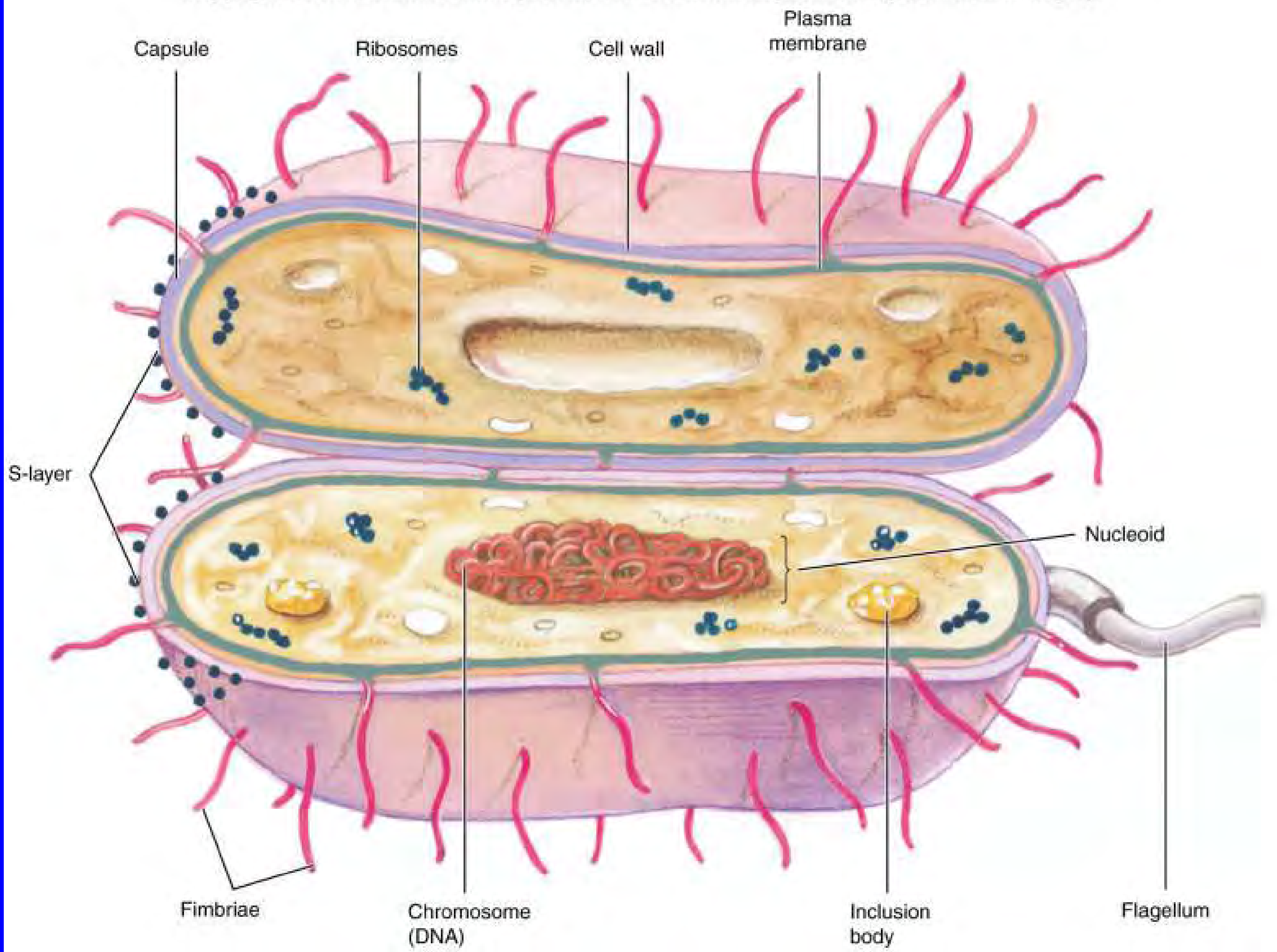


Figure 3.4

Table 3.1	Functions of Procaryotic Structures
Plasma membrane	Selectively permeable barrier, mechanical boundary of cell, nutrient and waste transport, location of many metabolic processes (respiration, photosynthesis), detection of environmental cues for chemotaxis
Gas vacuole	Buoyancy for floating in aquatic environments
Ribosomes	Protein synthesis
Inclusion bodies	Storage of carbon, phosphate, and other substances
Nucleoid	Localization of genetic material (DNA)
Periplasmic space	Contains hydrolytic enzymes and binding proteins for nutrient processing and uptake
Cell wall	Gives bacteria shape and protection from lysis in dilute solutions
Capsules and slime layers	Resistance to phagocytosis, adherence to surfaces
Fimbriae and pili	Attachment to surfaces, bacterial mating
Flagella	Movement
Endospore	Survival under harsh environmental conditions

Procaryotic Cell Membranes

- membranes are an absolute requirement for all living organisms
- plasma membrane encompasses the cytoplasm
- some procaryotes also have internal membrane systems

The Plasma Membrane

- contains lipids and proteins
  - lipids usually form a bilayer
  - proteins are embedded in or associated with lipids
- highly organized, asymmetric, flexible, and dynamic

The asymmetry of most membrane lipids

- polar ends
  - interact with water
  - hydrophilic
- nonpolar ends
  - insoluble in water
  - hydrophobic

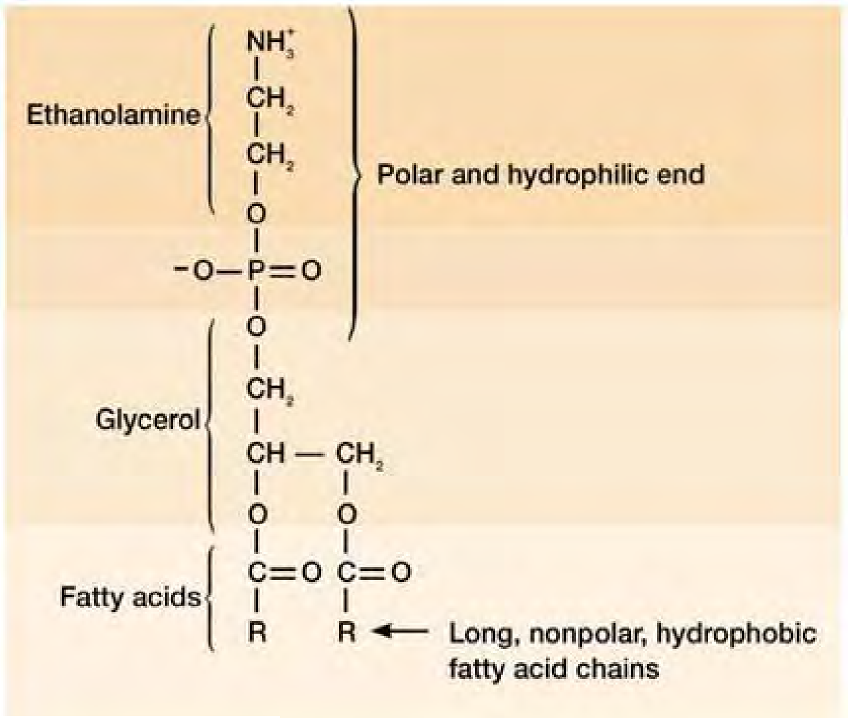


Figure 3.5

Other membrane lipids

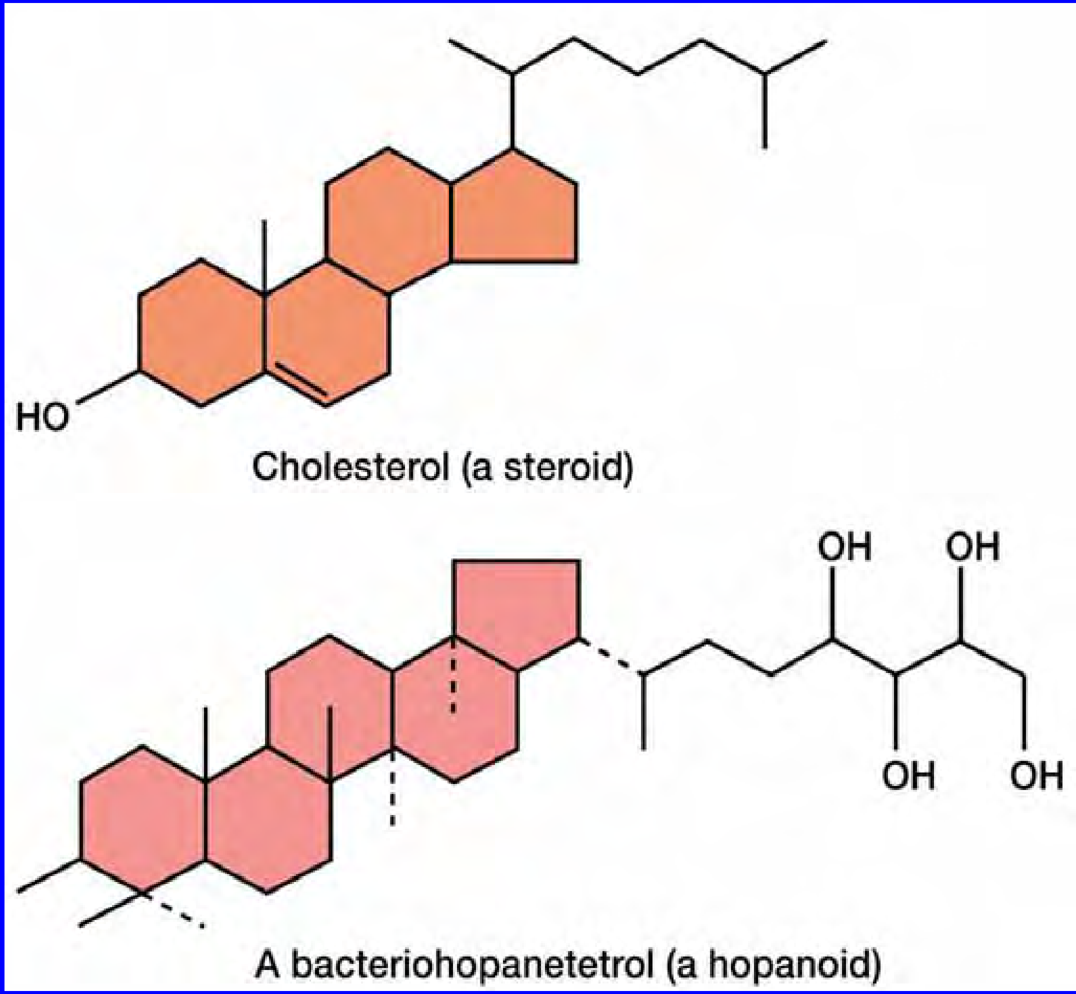


Figure 3.6

Membrane proteins

- **peripheral proteins**
  - **loosely associated with the membrane and easily removed**
- **integral proteins**
  - **embedded within the membrane and not easily removed**

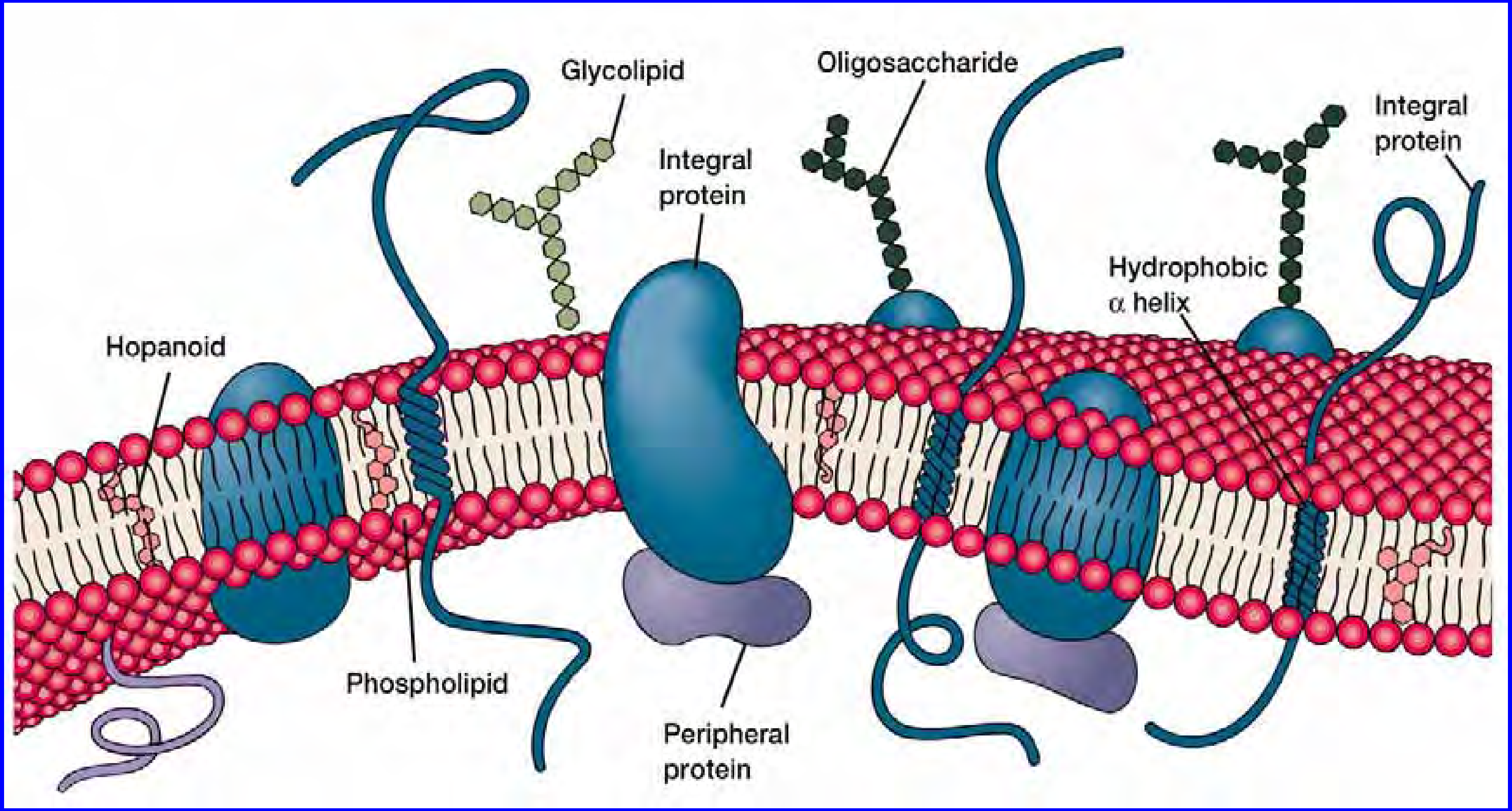


Figure 3.7

Fluid mosaic model of membrane structure

Archaeal membranes

- composed of unique lipids
- some have a monolayer structure instead of a bilayer structure

Functions of the plasma membrane

- separation of cell from its environment
- selectively permeable barrier
  - some molecules are allowed to pass into or out of the cell
  - transport systems aid in movement of molecules

More functions…

- location of crucial metabolic processes
- detection of and response to chemicals in surroundings with the aid of special receptor molecules in the membrane

Internal Membrane Systems

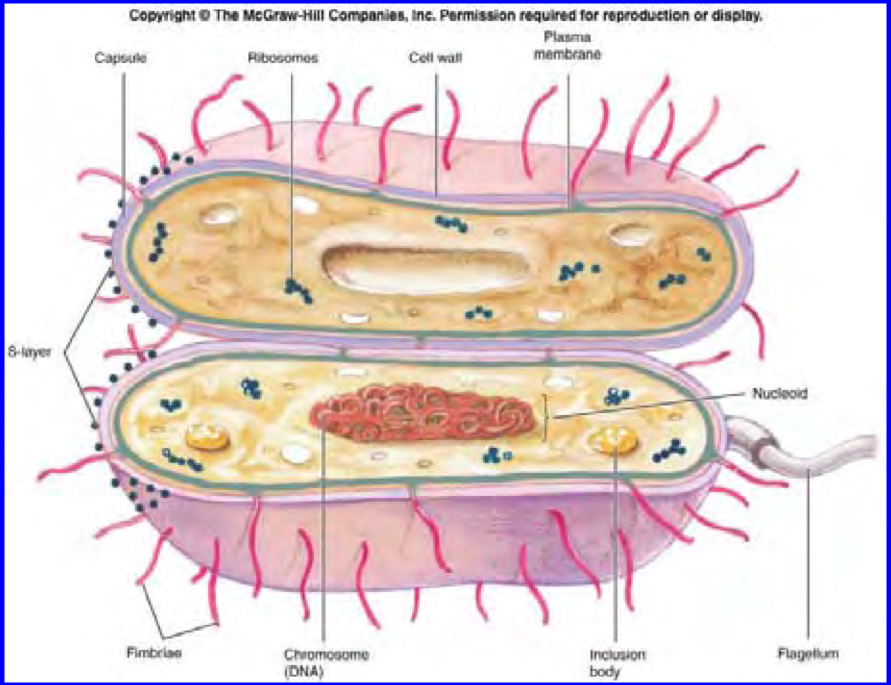
- mesosomes
  - may be invaginations of the plasma membrane
    - possible roles
      - cell wall formation during cell division
      - chromosome replication and distribution
      - secretory processes
  - may be artifacts of chemical fixation process

Other internal membrane systems

- complex in-foldings of the plasma membrane
  - observed in many photosynthetic bacteria and in procaryotes with high respiratory activity
  - may be aggregates of spherical vesicles, flattened vesicles, or tubular membranes

The Cytoplasmic Matrix

- substance between membrane and nucleoid
- packed with ribosomes and inclusion bodies
- highly organized with respect to protein location



Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

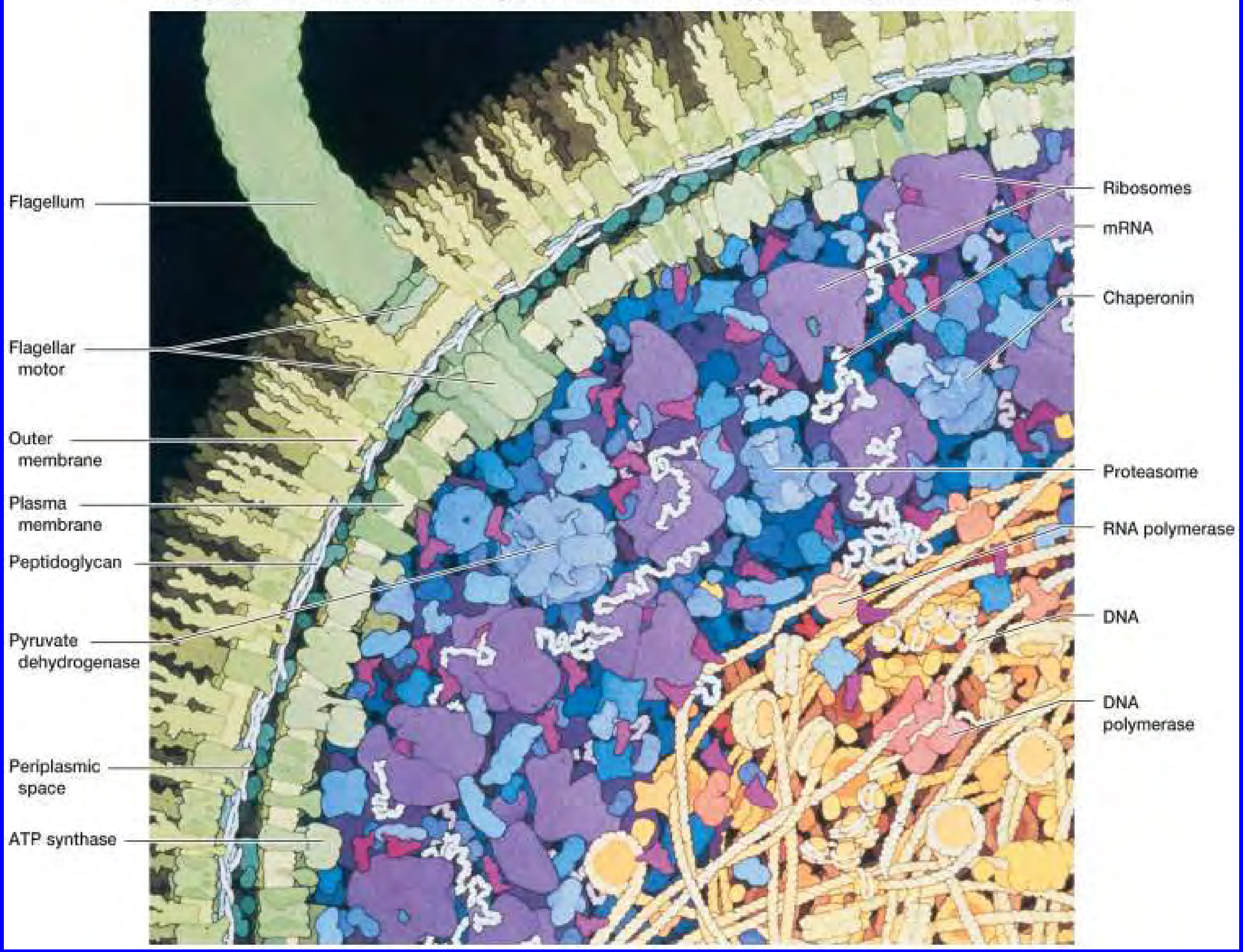


Figure 3.10

Inclusion Bodies

- granules of organic or inorganic material that are stockpiled by the cell for future use
- some are enclosed by a single-layered membrane
  – membranes vary in composition
  – some made of proteins; others contain lipids

Organic inclusion bodies

- **glycogen**
  - **polymer of glucose units**
- **poly-β-hydroxybutyrate (PHB)**
  - **polymers of β-hydroxybutyrate**

Organic inclusion bodies

- cyanophycin granules
  - large polypeptides containing about equal quantities of arginine and aspartic acid
- carboxysomes
  - contain the enzyme ribulose-1,5,-bisphosphate carboxylase

Organic inclusion bodies

- gas vacuoles
  - found in cyanobacteria and some other aquatic procaryotes
  - provide buoyancy
  - aggregates of hollow cylindrical structures called gas vesicles

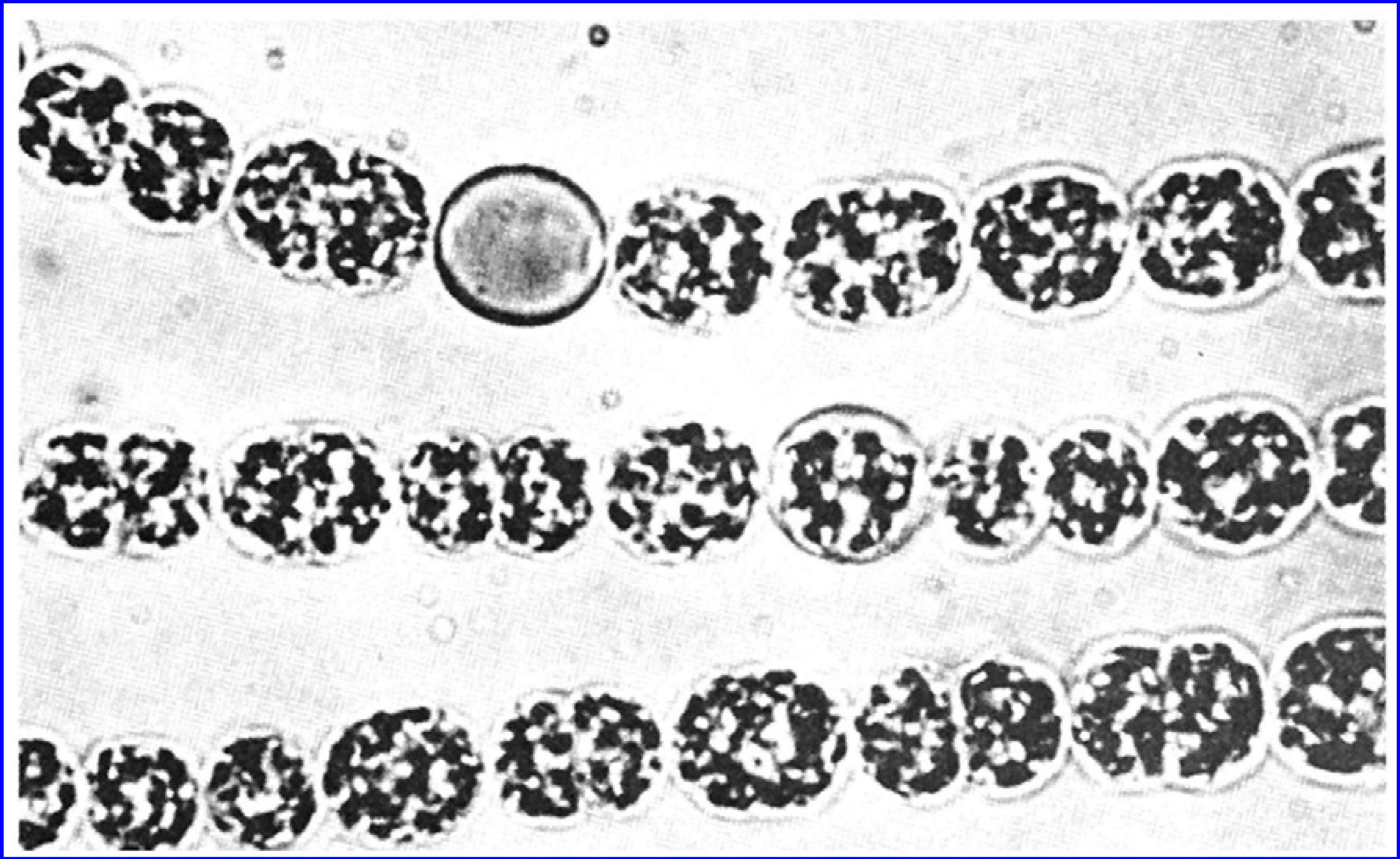


Figure 3.12a

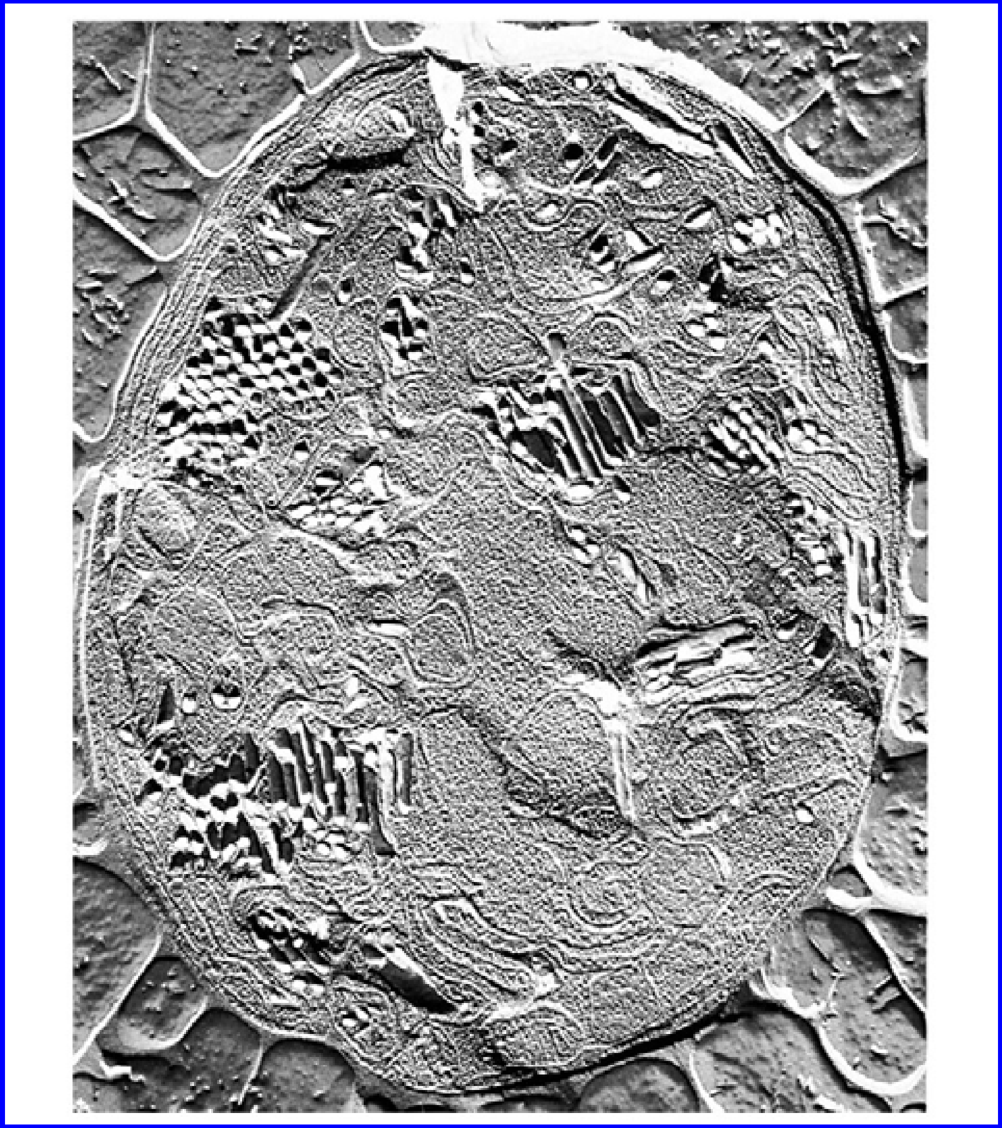
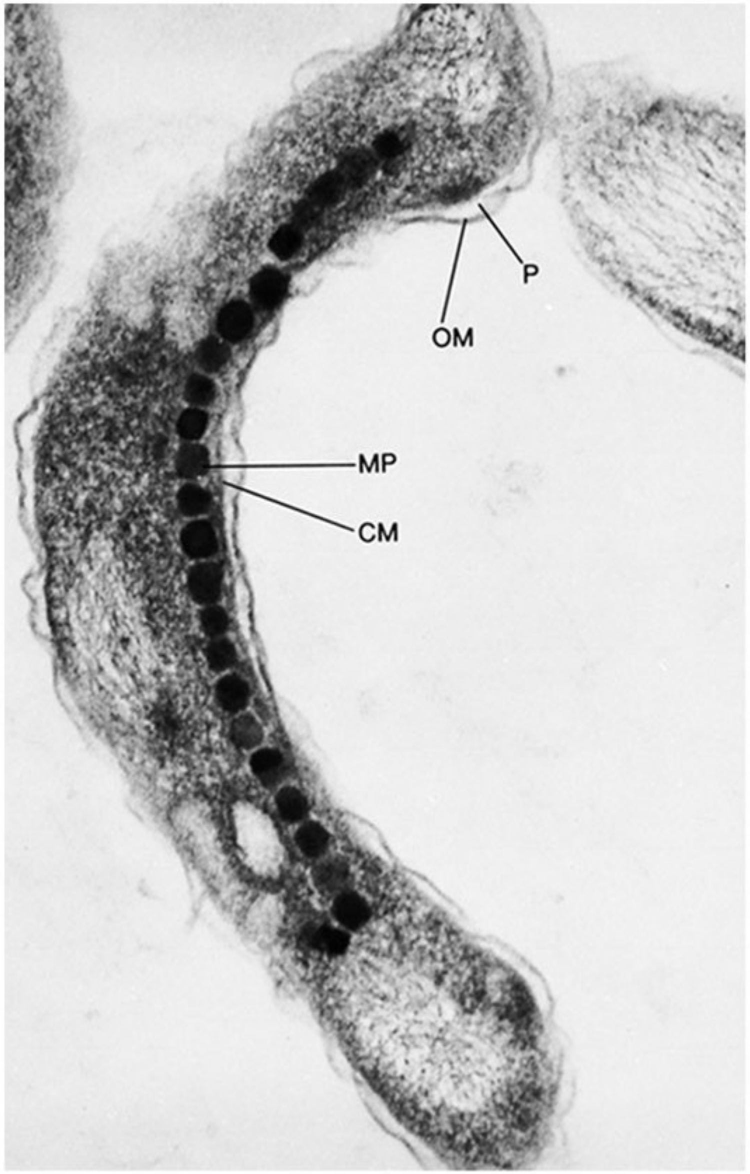


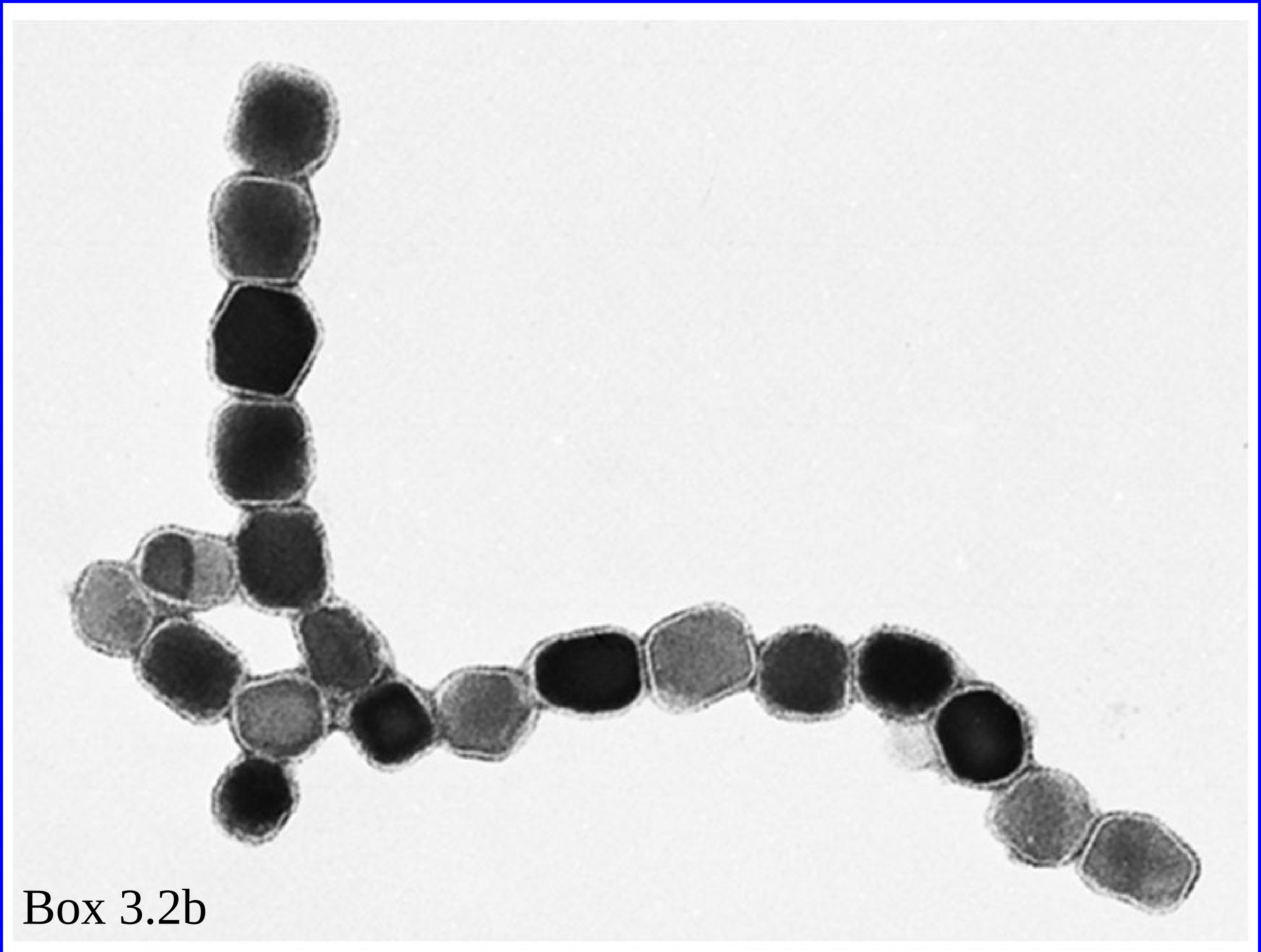
Figure 3.12b

Inorganic inclusion bodies

- polyphosphate granules
  - also called volutin granules and metachromatic granules
  - linear polymers of phosphates
- sulfur granules
- magnetosomes
  - contain iron in the form of magnetite
  - used to orient cells in magnetic fields



Box 3.2a


Box 3.2b

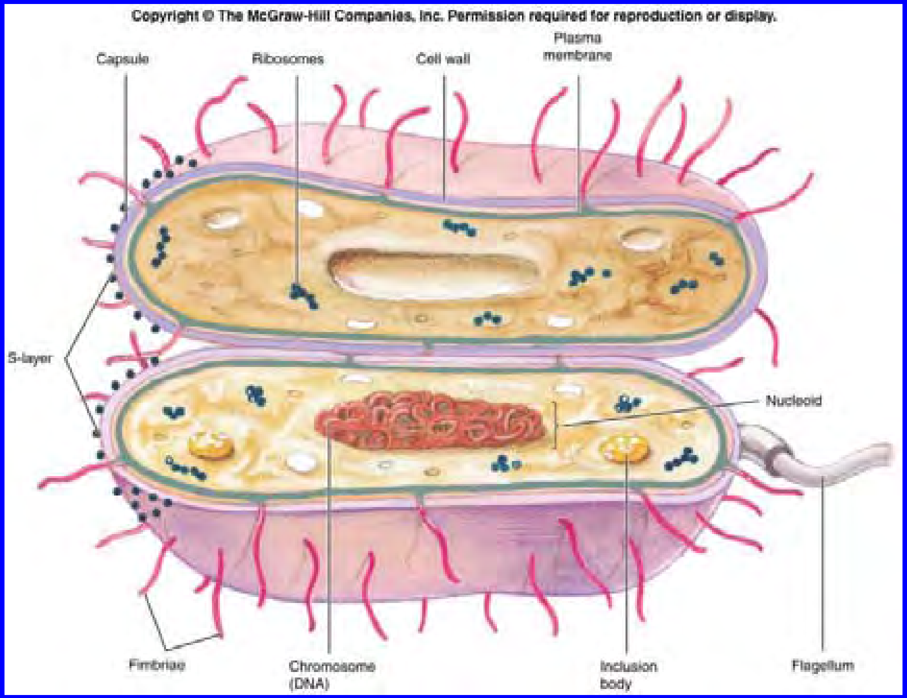
Box3.2c

Ribosomes

- complex structures consisting of protein and RNA
- sites of protein synthesis
- smaller than eucaryotic ribosomes
  - procaryotic ribosomes $\Rightarrow$ 70S
  - eucaryotic ribosomes $\Rightarrow$ 80S
    - S = Svedburg unit

The Nucleoid

- irregularly shaped region
- location of chromosome
  - usually 1/cell
- not membrane-bound



In actively growing cells, the nucleoid has projections; these probably contain DNA being actively transcribed

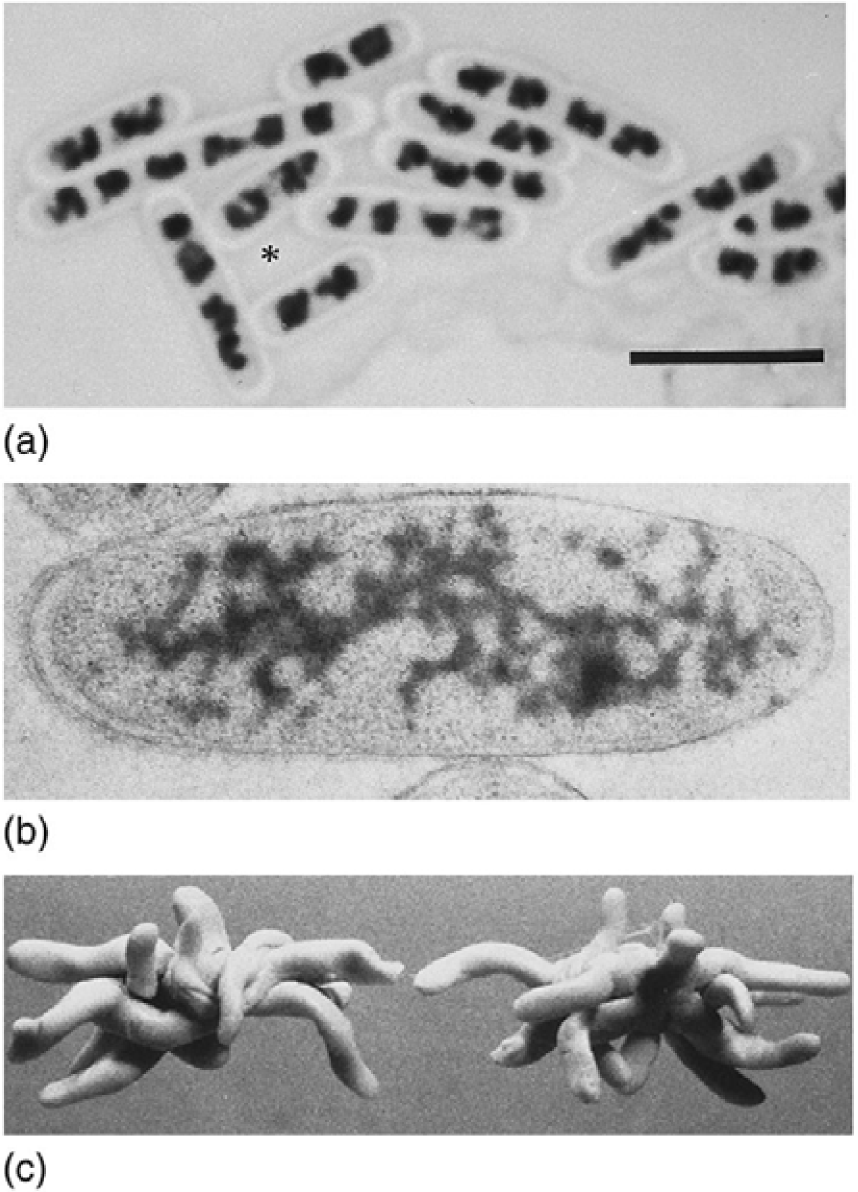


Figure 3.14

The procaryotic chromosome

- a closed circular, double-stranded DNA molecule
- looped and coiled extensively
- nucleoid proteins probably aid in folding
  - nucleoid proteins differ from histones

Unusual nucleoids

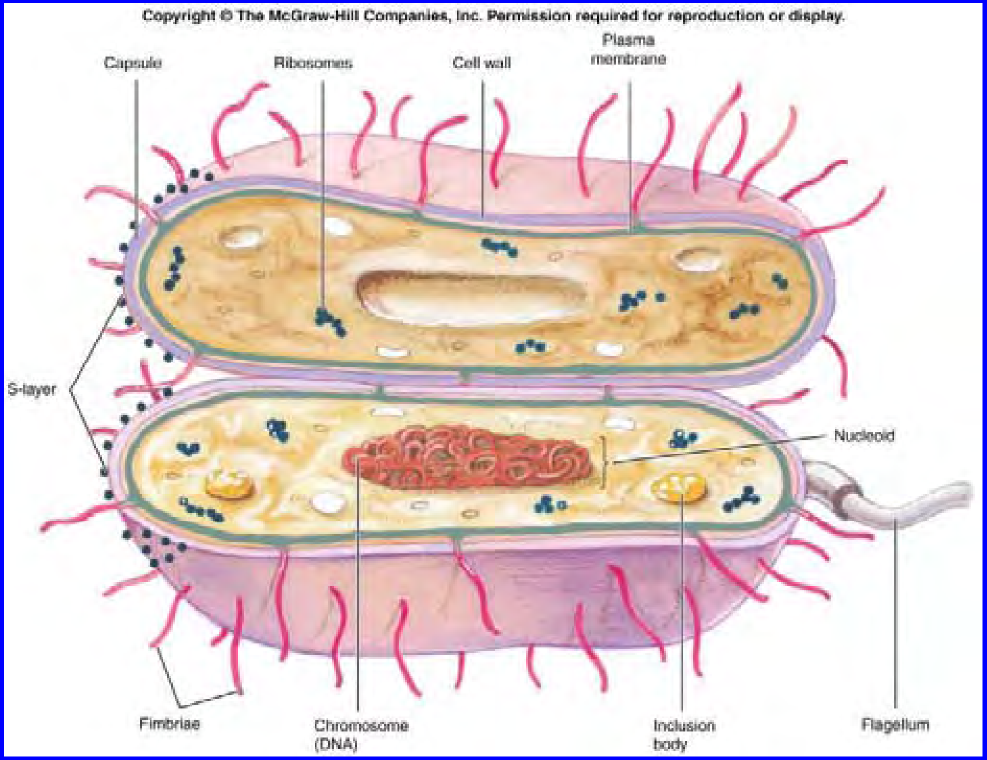
- some procaryotes have > 1 chromosome
- some procaryotes have chromosomes composed of linear double-stranded DNA
- a few genera have membrane-delimited nucleoids

Plasmids

- usually small, closed circular DNA molecules
- exist and replicate independently of chromosome
- not required for growth and reproduction
- may carry genes that confer selective advantage (e.g., drug resistance)

The Procaryotic Cell Wall

- rigid structure that lies just outside the plasma membrane



Functions of cell wall

- provides characteristic shape to cell
- protects the cell from osmotic lysis
- may also contribute to pathogenicity
- may also protect cell from toxic substances

Cell walls of Bacteria

- Bacteria are divided into two major groups based on the response to Gram-stain procedure.
  - gram-positive bacteria stain purple
  - gram-negative bacteria stain pink
- staining reaction due to cell wall structure

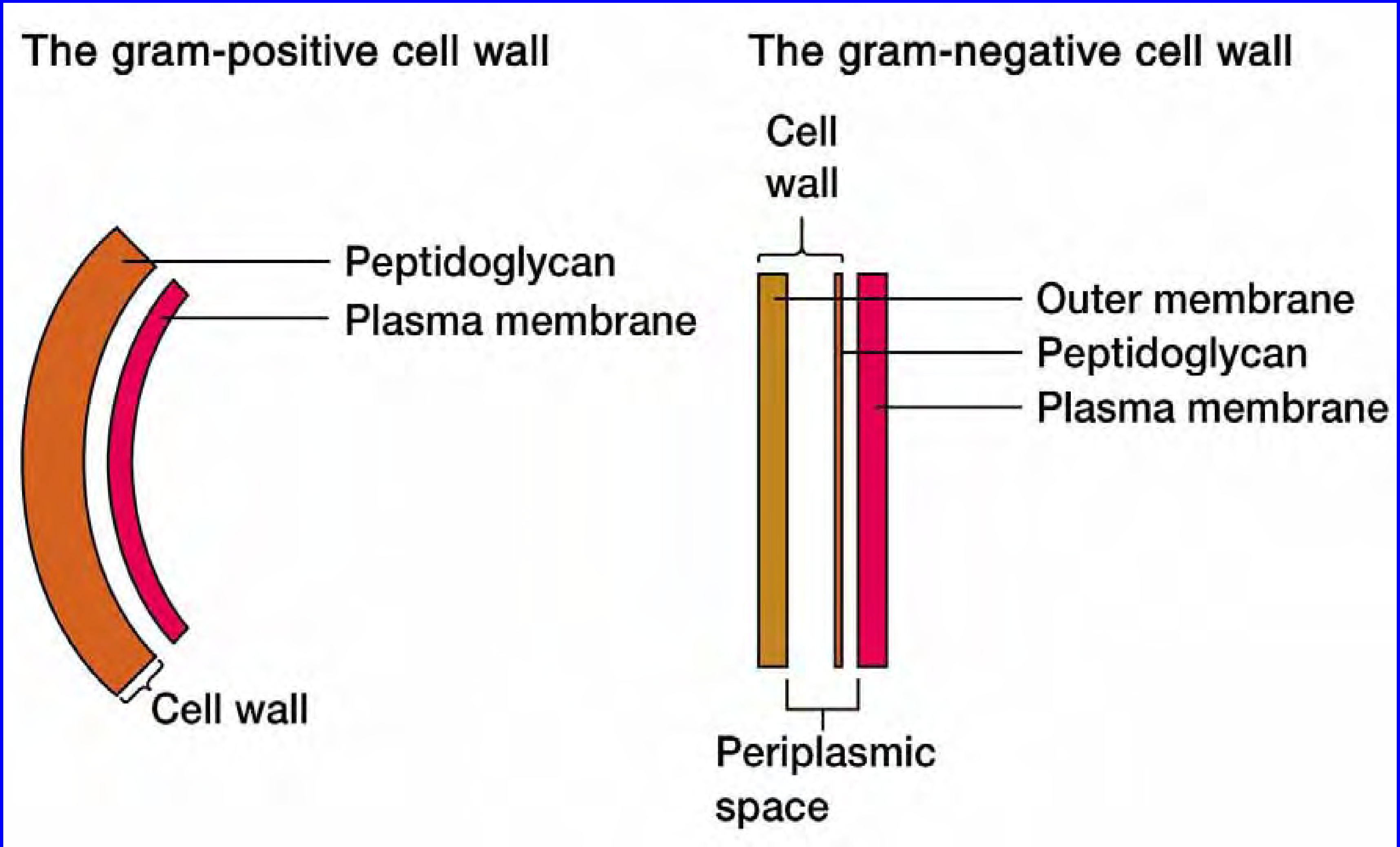

The gram-positive cell wall
Peptidoglycan
Plasma membrane
Cell wall
The gram-negative cell wall
Cell wall
Outer membrane
Peptidoglycan
Plasma membrane
Periplasmic space

Figure 3.15

Periplasmic space

- gap between plasma membrane and cell wall (gram-positive bacteria) or between plasma membrane and outer membrane (gram-negative bacteria)
- periplasm
  - substance that occupies periplasmic space

Periplasmic enzymes

- found in periplasm of gram-negative bacteria
- some of their functions
  - nutrient acquisition
  - electron transport
  - peptidoglycan synthesis
  - modification of toxic compounds

Exoenzymes

- secreted by gram-positive bacteria
- perform many of the same functions that periplasmic enzymes do for gram-negative bacteria

Peptidoglycan Structure

- important component of both gram-positive and gram-negative bacteria
- polysaccharide formed from peptidoglycan subunits
- two alternating sugars form backbone
  - *N*-acetylglucosamine
  - *N*-acetylmuramic acid

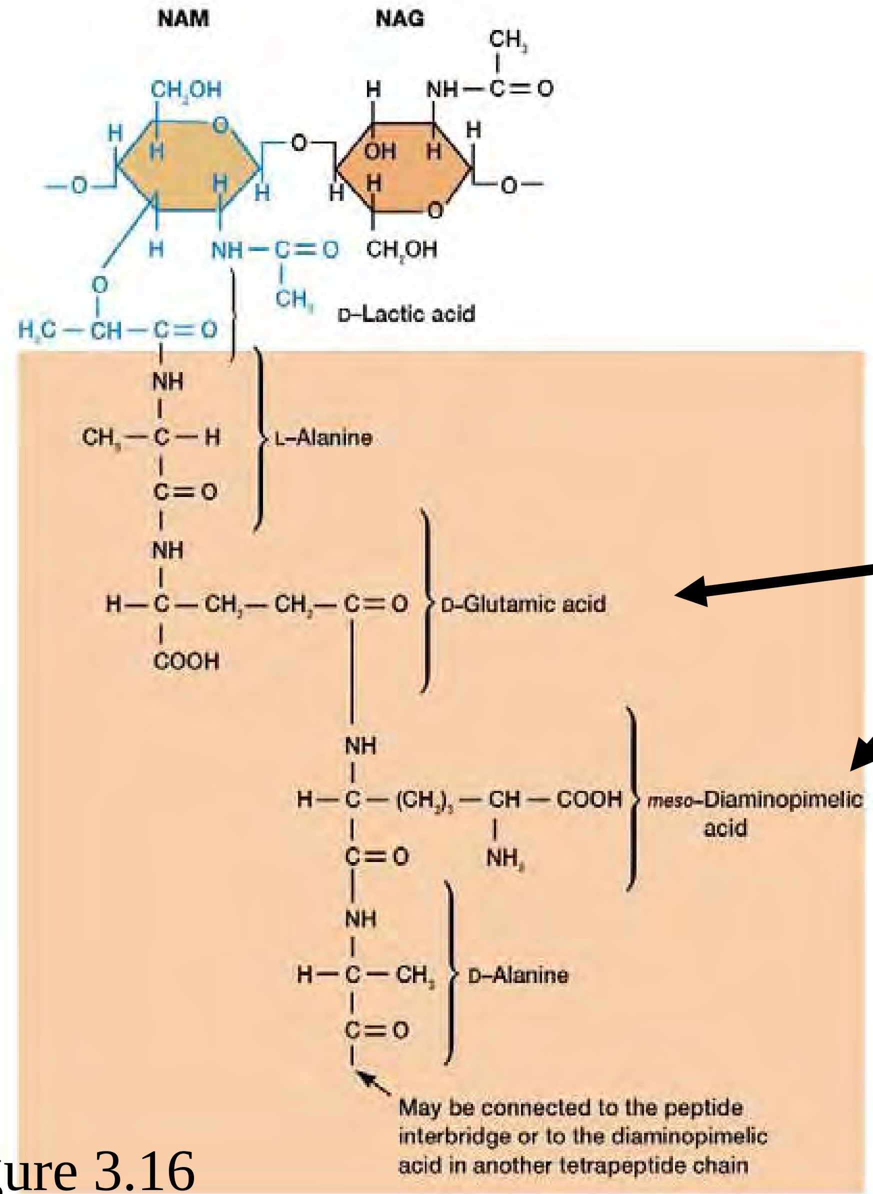


Figure 3.16

some amino acids are not observed in proteins

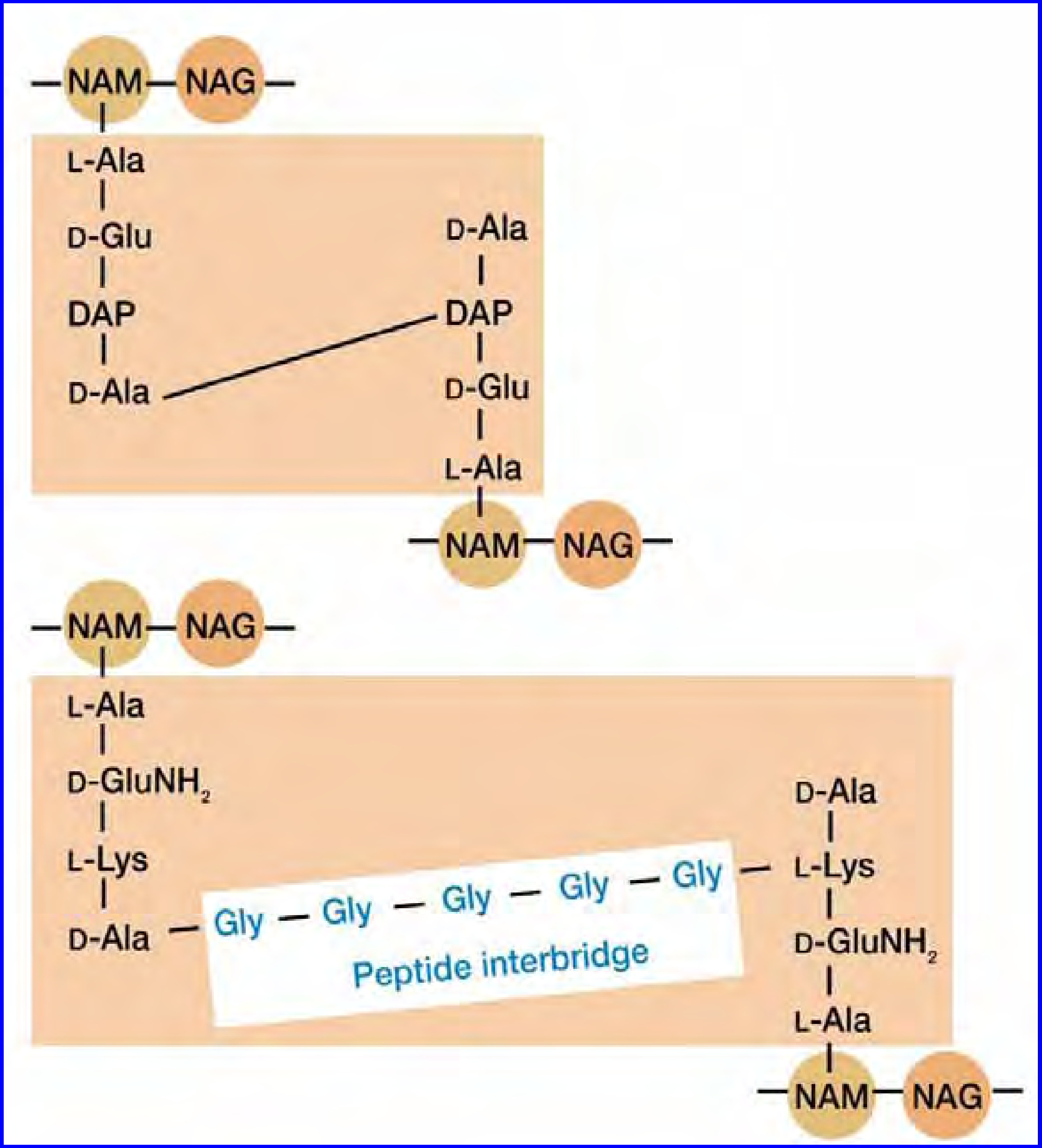

NAM
NAG
L-Ala
D-Glu
DAP
D-Ala
D-Ala
DAP
D-Glu
L-Ala
NAM
NAG
NAM
NAG
L-Ala
D-GluNH$_2$
L-Lys
D-Ala
Gly — Gly — Gly — Gly — Gly
Peptide interbridge
D-Ala
L-Lys
D-GluNH$_2$
L-Ala
NAM
NAG

Figure 3.18

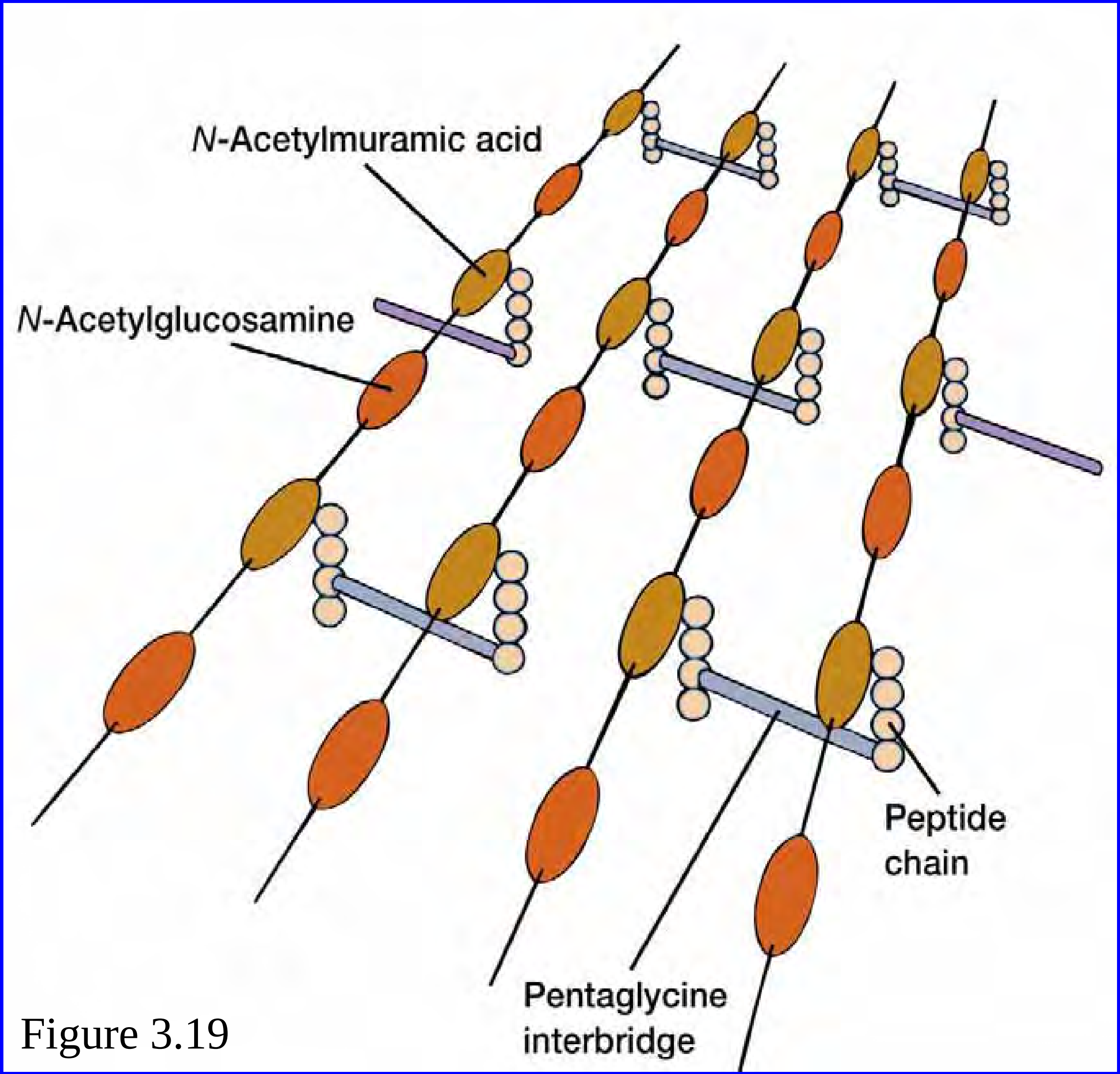

N-Acetylmuramic acid
N-Acetylglucosamine
Peptide chain
Pentaglycine interbridge

Figure 3.19

Gram-Positive Cell Walls

- composed primarily of peptidoglycan
- may also contain large amounts of teichoic acids
- some gram-positive bacteria have layer of proteins on surface of peptidoglycan

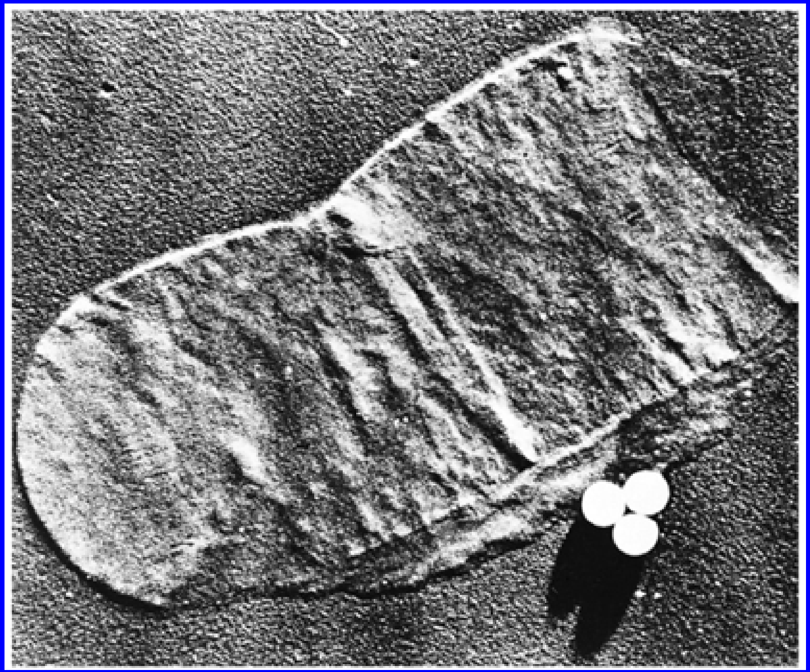


Figure 3.20

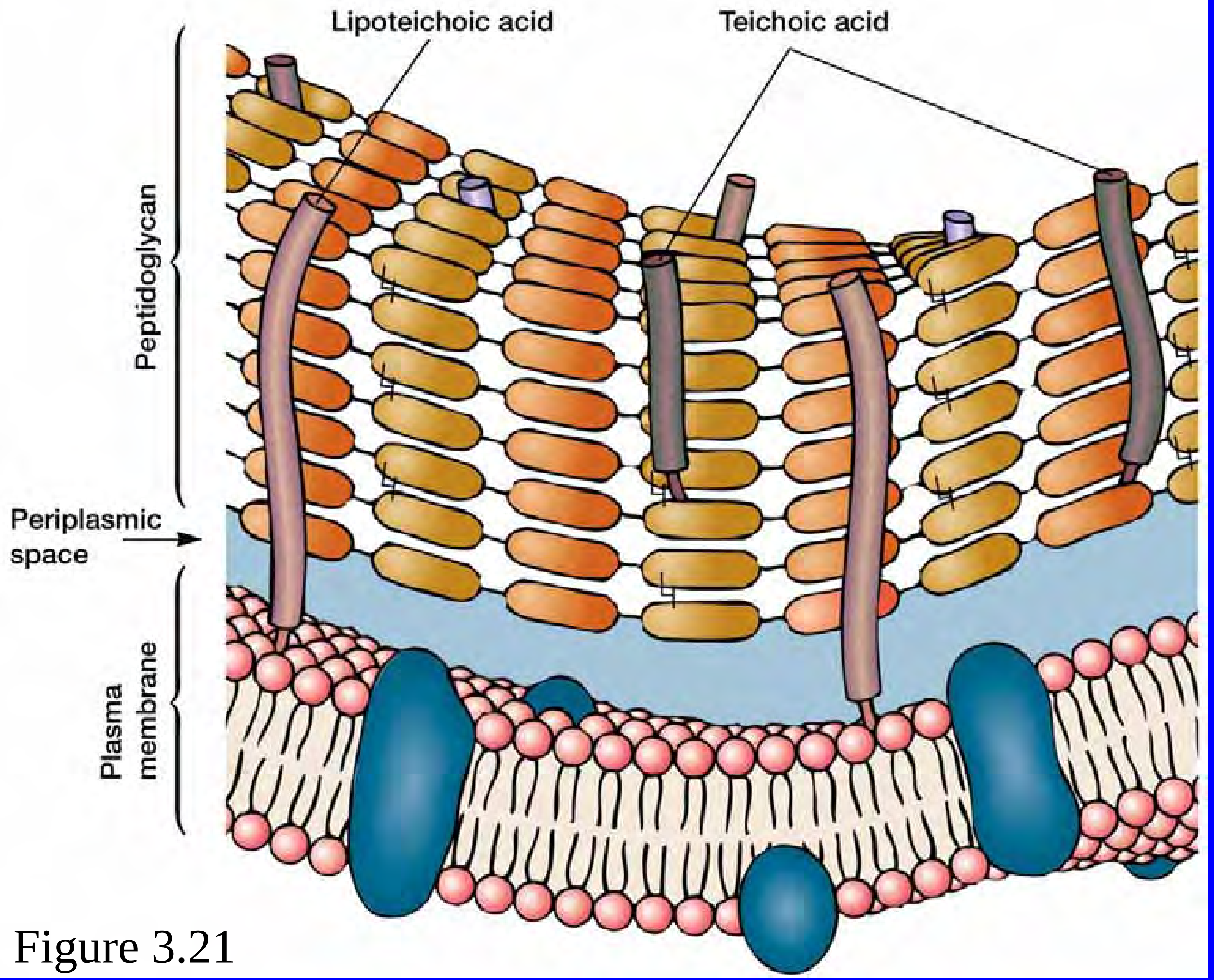

Lipoteichoic acid
Teichoic acid
Peptidoglycan
Periplasmic space
Plasma membrane

Figure 3.21

teichoic acids

• polymers of glycerol or ribitol joined by phosphate groups

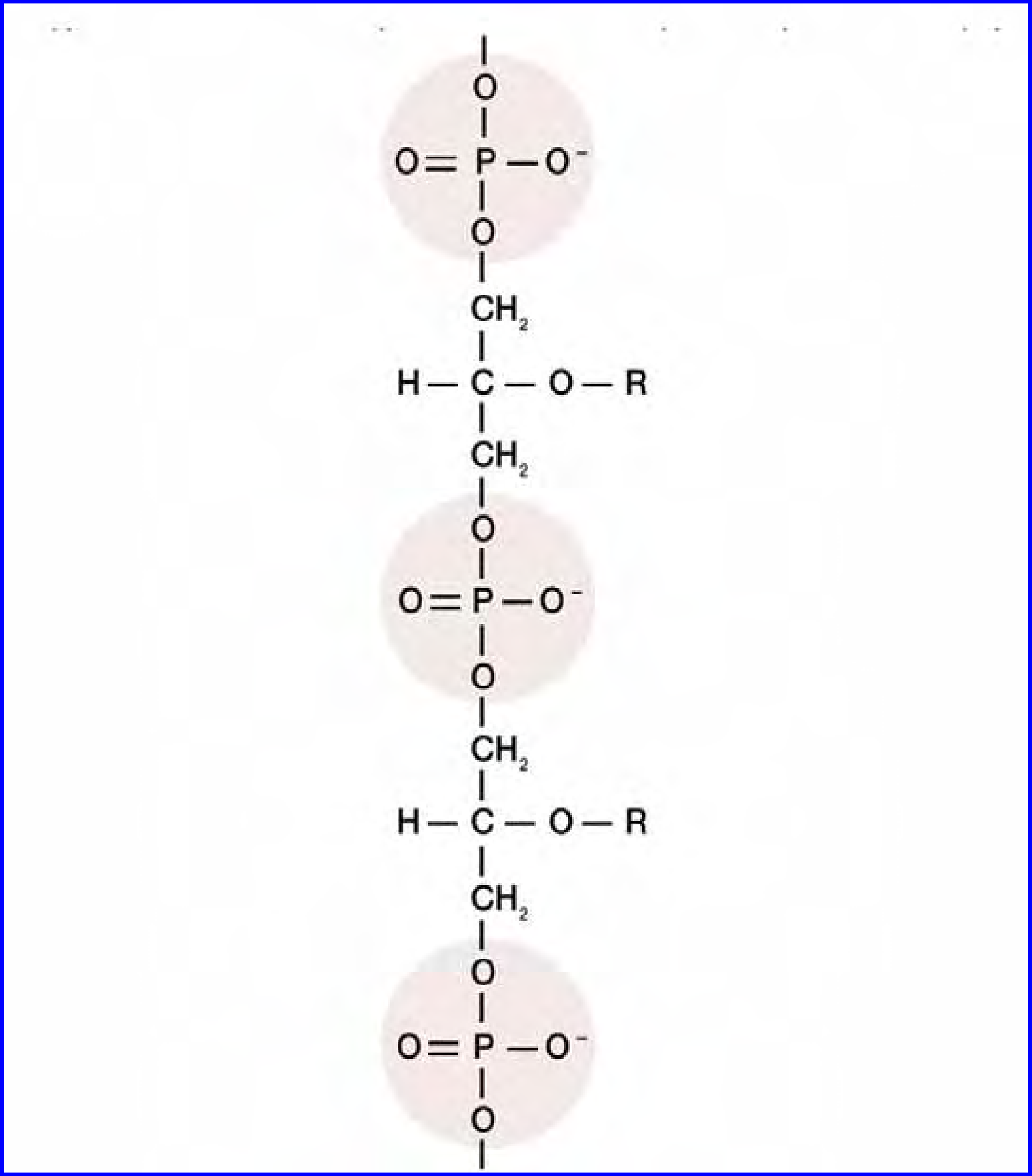
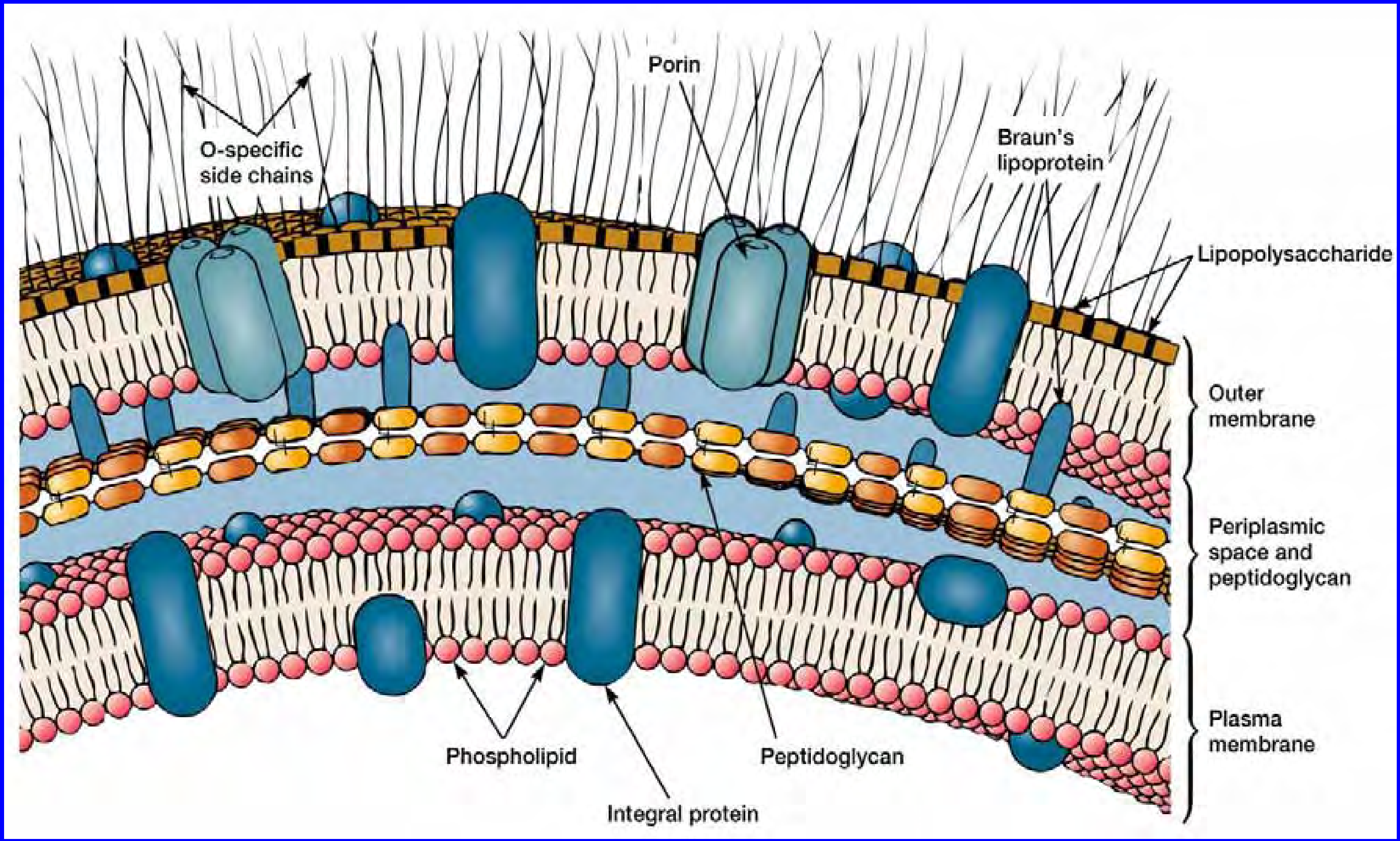


Figure 3.22

Gram-Negative Cell Walls

- consist of a thin layer of peptidoglycan surrounded by an **outer membrane**
- outer membrane composed of lipids, lipoproteins, and **lipopolysaccharide** (**LPS**)
- no teichoic acids



O-specific
side chains
Porin
Braun's
lipoprotein
Lipopolysaccharide
Outer
membrane
Periplasmic
space and
peptidoglycan
Plasma
membrane
Phospholipid
Peptidoglycan
Integral protein

Figure 3.23

Important connections

- **Braun's lipoproteins connect outer membrane to peptidoglycan**
- **Adhesion sites**
  - **sites of direct contact (possibly true membrane fusions) between plasma membrane and outer membrane**
  - **substances may move directly into cell through adhesion sites**

Lipopolysaccharides (LPSs)

- consist of three parts
  - lipid A
  - core polysaccharide
  - O side chain (O antigen)

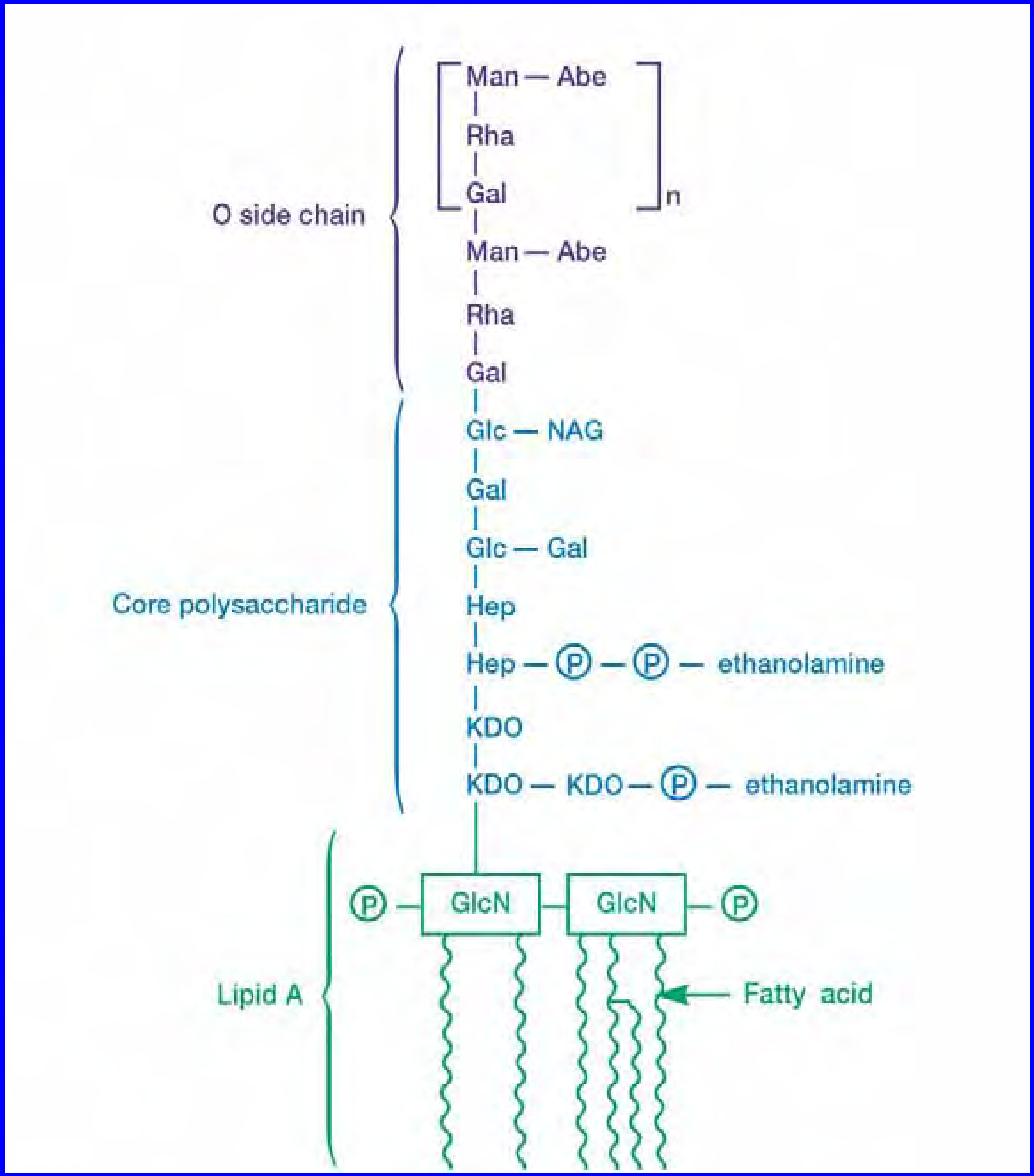

Man — Abe
Rha
Gal
n
O side chain
Man — Abe
Rha
Gal
Glc — NAG
Gal
Glc — Gal
Core polysaccharide
Hep
Hep — P — P — ethanolamine
KDO
KDO — KDO — P — ethanolamine
P
GlcN
GlcN
P
Lipid A
Fatty acid

Figure 3.25

Importance of LPS

- protection from host defenses (O antigen)
- contributes to negative charge on cell surface (core polysaccharide)
- helps stabilize outer membrane structure (lipid A)
- can act as an exotoxin (lipid A)

Other characteristics of outer membrane

- **more permeable than plasma membrane due to presence of porin proteins and transporter proteins**
  - **porin proteins form channels through which small molecules (600-700 daltons) can pass**

The Mechanism of Gram Staining

- thought to involve constriction of the thick peptidoglycan layer of gram-positive cells
  - constriction prevents loss of crystal violet during decolorization step
- thinner peptidoglycan layer of gram-negative bacteria does not prevent loss of crystal violet

The Cell Wall and Osmotic Protection

- **osmosis**
  - **movement of water across selectively permeable membrane from dilute solutions to more concentrated solutions**
- **cells are often in hypotonic solutions**

$$[\text{solute}]_{\text{outside cell}} < [\text{solute}]_{\text{inside cell}}$$

The Cell Wall and Osmotic Protection

- osmotic lysis
  - can occur when cells are in hypotonic solutions
  - movement of water into cell causes swelling and lysis due to osmotic pressure
- cell wall protects against osmotic lysis

Cell walls do not protect against plasmolysis

- **plasmolysis**
  - occurs when cells are in hypertonic solutions

    $[\text{solute}]_{\text{outside cell}} > [\text{solute}]_{\text{inside cell}}$
  - water moves out of cell causing cytoplasm to shrivel and pull away from cell wall

Practical importance of plasmolysis and osmotic lysis

- plasmolysis
  - useful in food preservation
  - e.g., dried foods and jellies
- osmotic lysis
  - basis of lysozyme and penicillin action

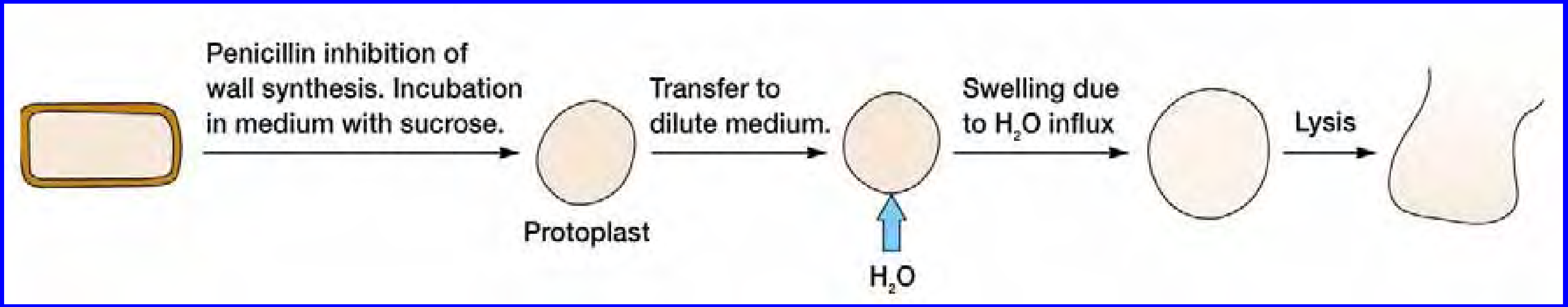


Figure 3.26

- protoplast – cell completely lacking cell wall
- spheroplast – cell with some cell wall remaining

Archaeal cell walls

- **lack peptidoglycan**
- **can be composed of proteins, glycoproteins, or polysaccharides**

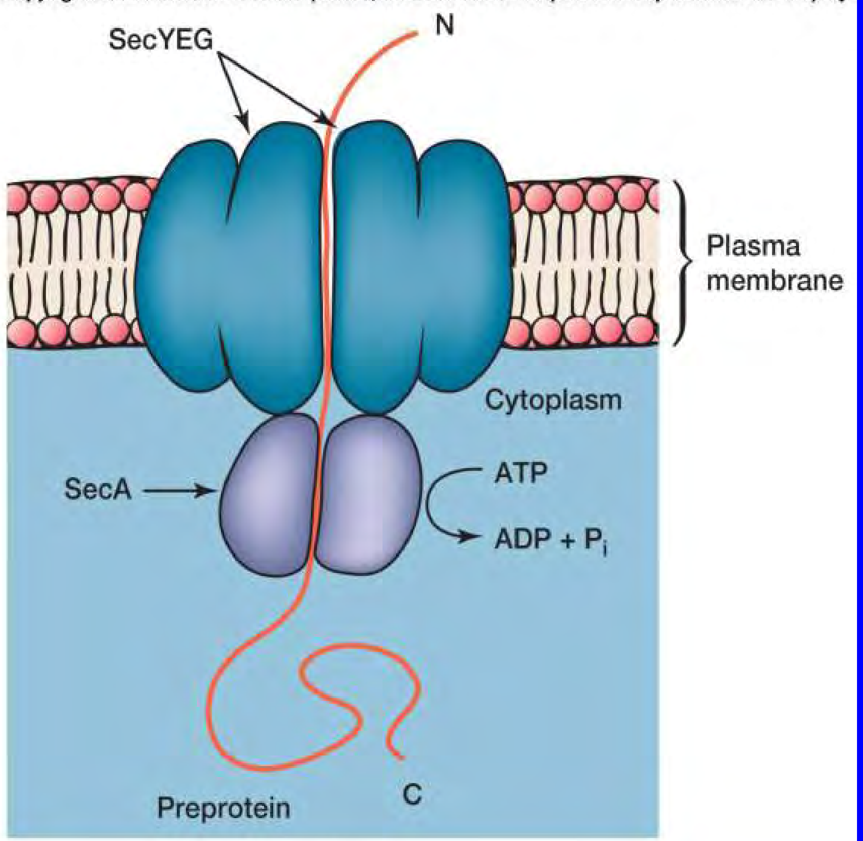
Protein Secretion in Procaryotes

- numerous protein secretion pathways have been identified
- four major pathways are:
  - Sec-dependent pathway
  - type II pathway
  - type I (ABC) protein secretion pathway
  - type III protein secretion pathway

Sec-Dependent Pathway

- also called **general secretion pathway**
- translocates proteins from cytoplasm across or into plasma membrane
- secreted proteins synthesized as preproteins having amino-terminal **signal peptide**
  - signal peptide delays protein folding
  - chaperone proteins keep preproteins unfolded
- **translocon** transfers protein and removes signal peptide

Sec-Dependent Pathway



(a)

Figure 3.27a

Type II Protein Secretion Pathway

- transports proteins from periplasmic across outer membrane
- observed in some gram-negative bacteria, including some pathogens
- complex systems consisting of up to 12-14 proteins
  - most are integral membrane proteins

Type I Protein Secretion Pathway

- also called ABC protein secretion pathway
- transports proteins from cytoplasm across both plasma membrane and outer membrane
- secreted proteins have C-terminal secretion signals
- proteins that comprise type I systems form channels through membranes
- translocation driven by both ATP hydrolysis and proton motive force

Type I Protein Secretion Pathway

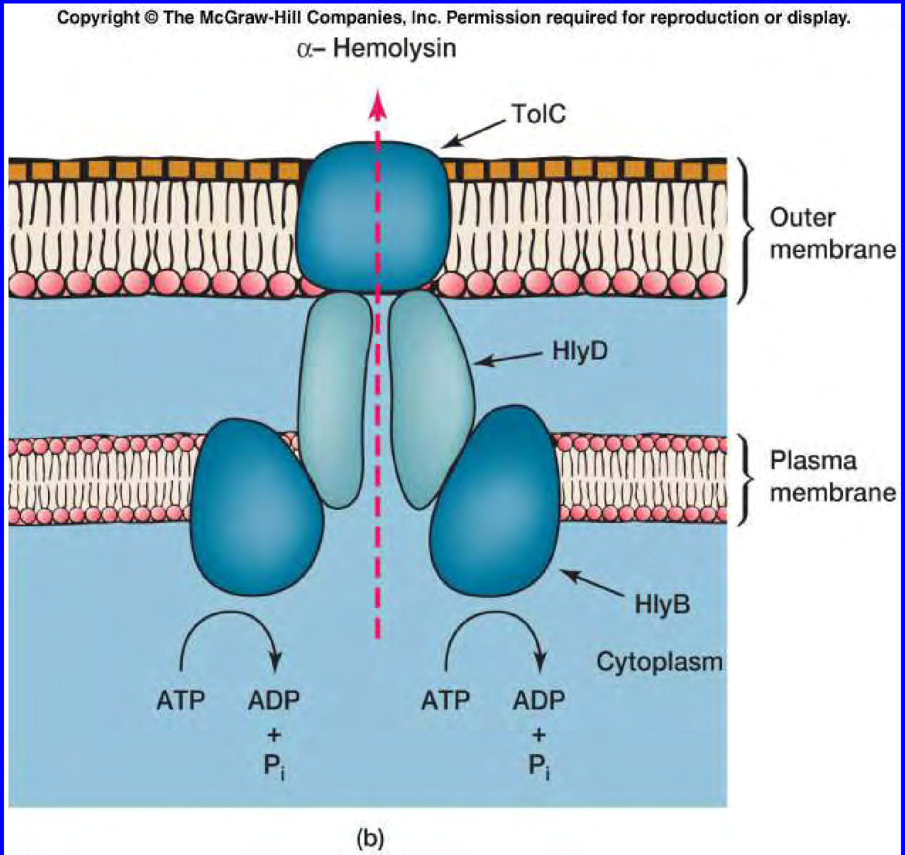


Figure 3.27b

Type III Protein Secretion Pathway

- secretes virulence factors of gram-negative bacteria from cytoplasm, across both plasma membrane and outer membrane, and into host cell
- some type III secretion machinery is needle-shaped
  - secreted proteins thought to move through a translocation channel

Type III Protein Secretion Pathway

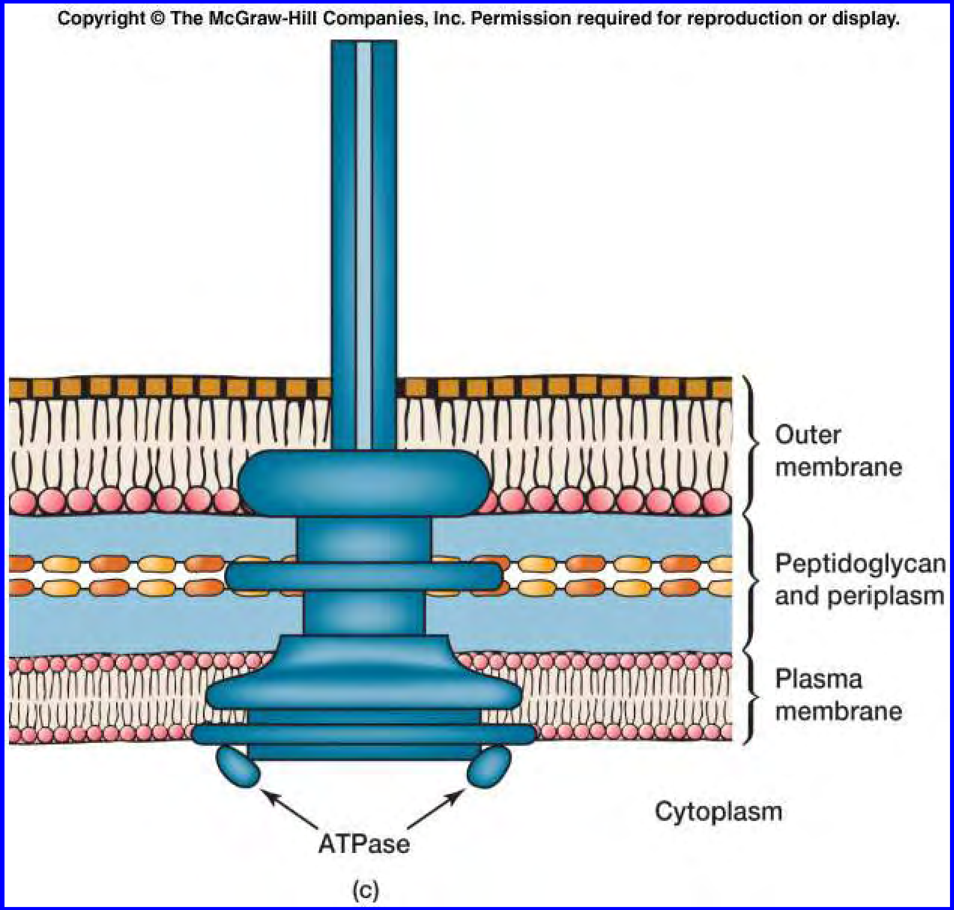
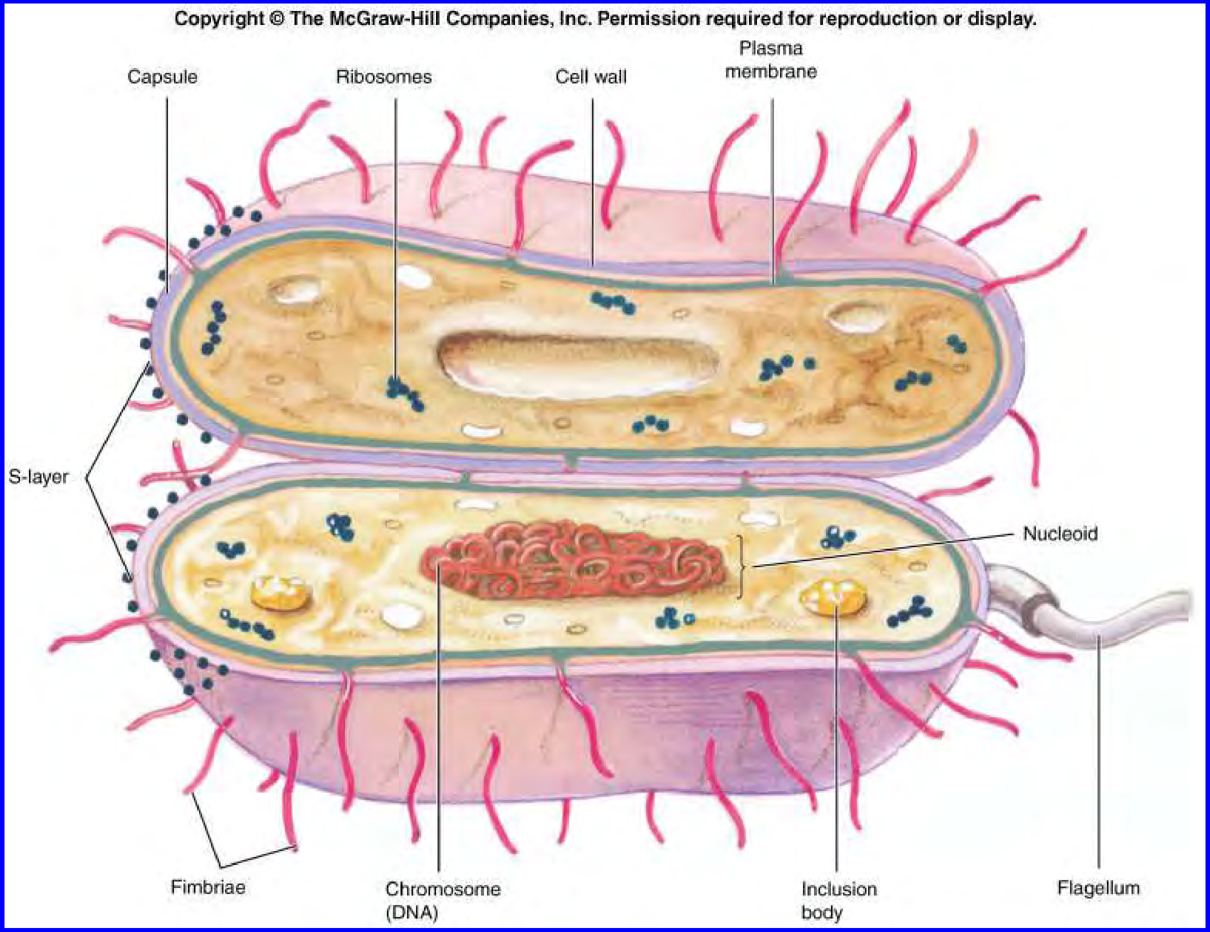


Figure 3.27 c

Components External to Cell Wall



Capsules, Slime Layers, and S-Layers

- layers of material lying outside the cell wall
  - capsules
    - usually composed of polysaccharides
    - well organized and not easily removed from cell
  - slime layers
    - similar to capsules except diffuse, unorganized and easily removed

Capsules, Slime Layers, and S-Layers

- glycocalyx
  - network of polysaccharides extending from the surface of the cell
  - a capsule or slime layer composed of polysaccharides can also be referred to as a glycocalyx

Capsules, Slime Layers, and S-Layers

- S-layers
  - regularly structured layers of protein or glycoprotein
  - common among Archaea, where they may be the only structure outside the plasma membrane

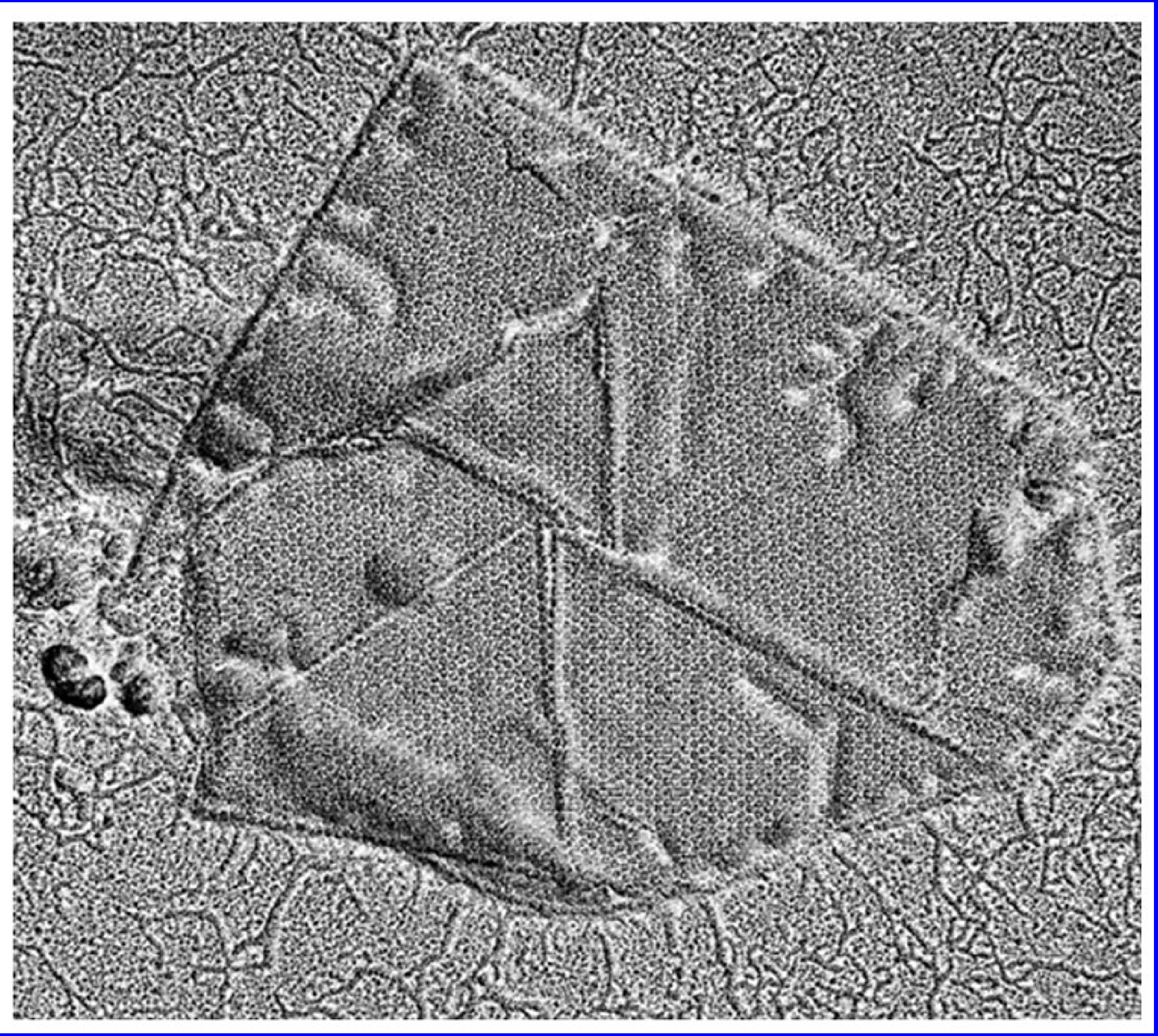


Figure 3.30

Functions of capsules, slime layers, and S-layers

- **protection from host defenses (e.g., phagocytosis)**
- **protection from harsh environmental conditions (e.g., desiccation)**
- **attachment to surfaces**

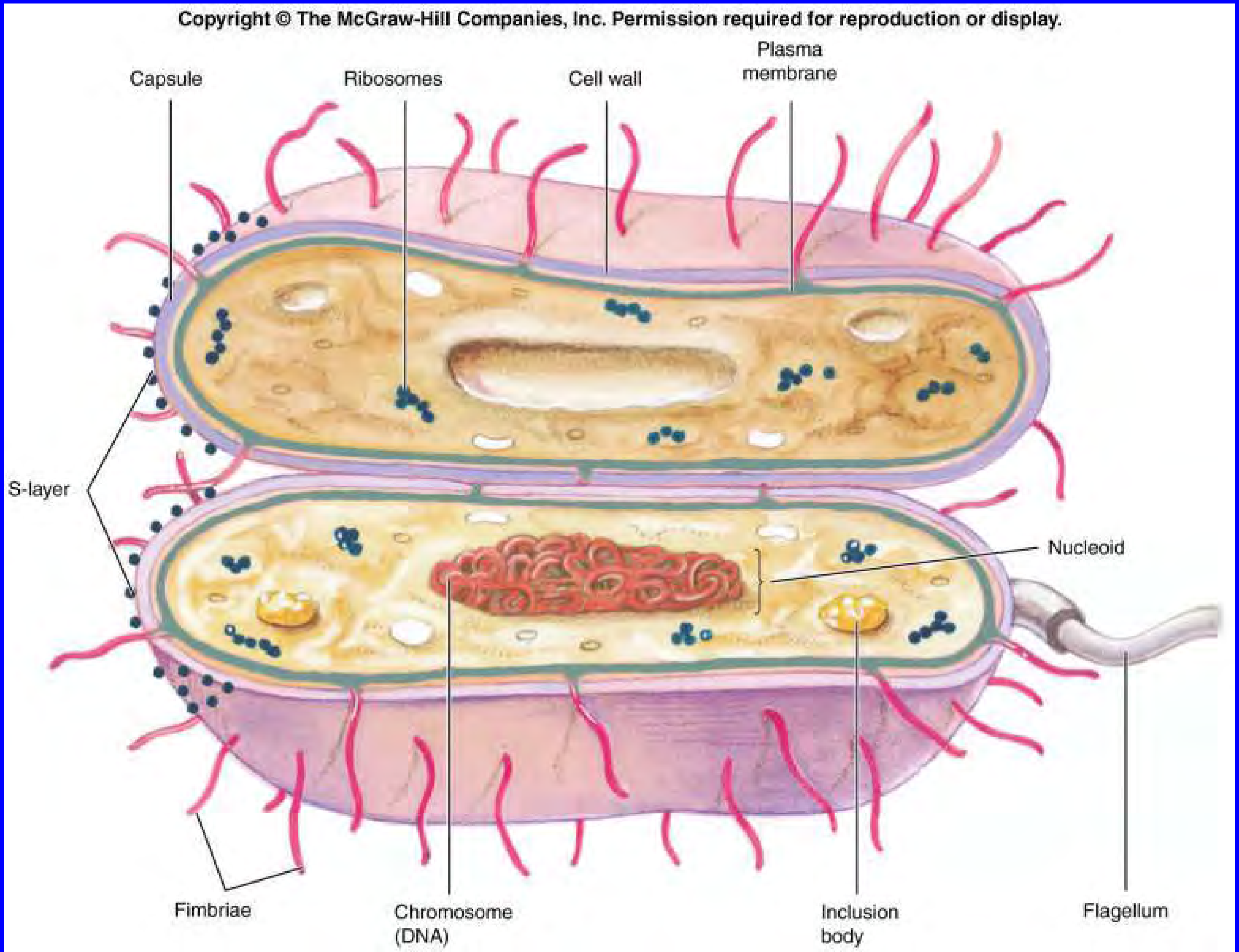
More functions…

- protection from viral infection or predation by bacteria
- protection from chemicals in environment (e.g., detergents)
- motility of gliding bacteria
- protection against osmotic stress

Pili and Fimbriae

- **fimbriae** (s., **fimbria**)
  - short, thin, hairlike, proteinaceous appendages
    - up to 1,000/cell
  - mediate attachment to surfaces
  - some (type IV fimbriae) required for twitching motility or gliding motility that occurs in some bacteria
- **sex pili** (s., **pilus**)
  - similar to fimbriae except longer, thicker, and less numerous (1-10/cell)
  - required for mating

Flagella and Motility



Patterns of arrangement

- **monotrichous** – one flagellum
- **polar flagellum** – flagellum at end of cell
- **amphitrichous** – one flagellum at each end of cell
- **lophotrichous** – cluster of flagella at one or both ends
- **peritrichous** – spread over entire surface of cell

Flagellar Ultrastructure

- 3 parts
  - filament
  - basal body
  - hook

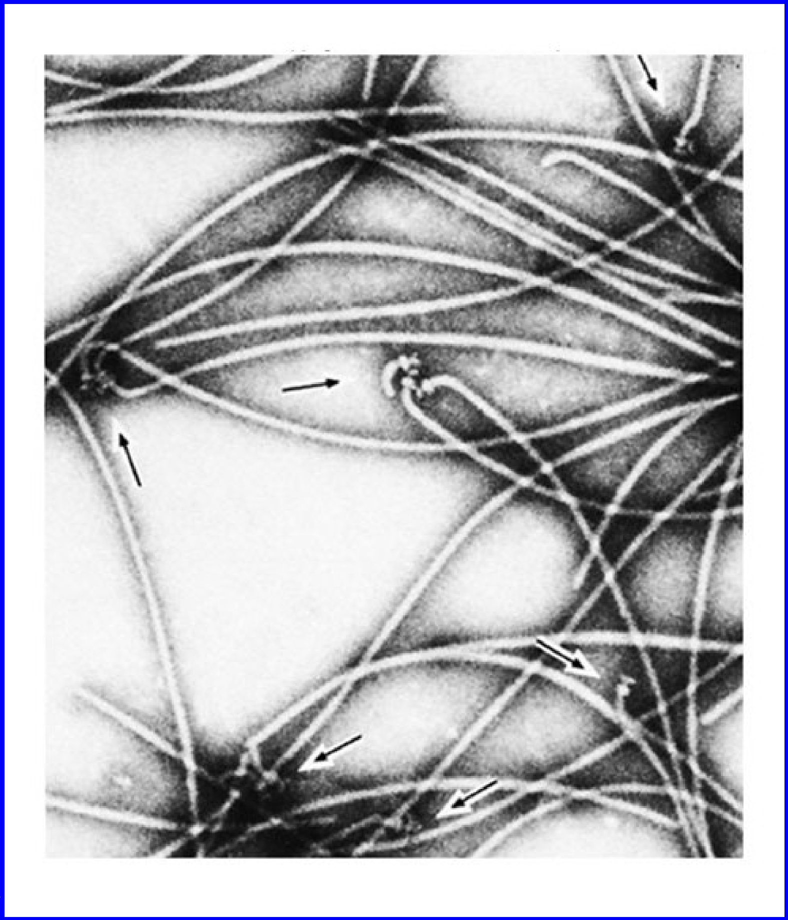


Figure 3.33a

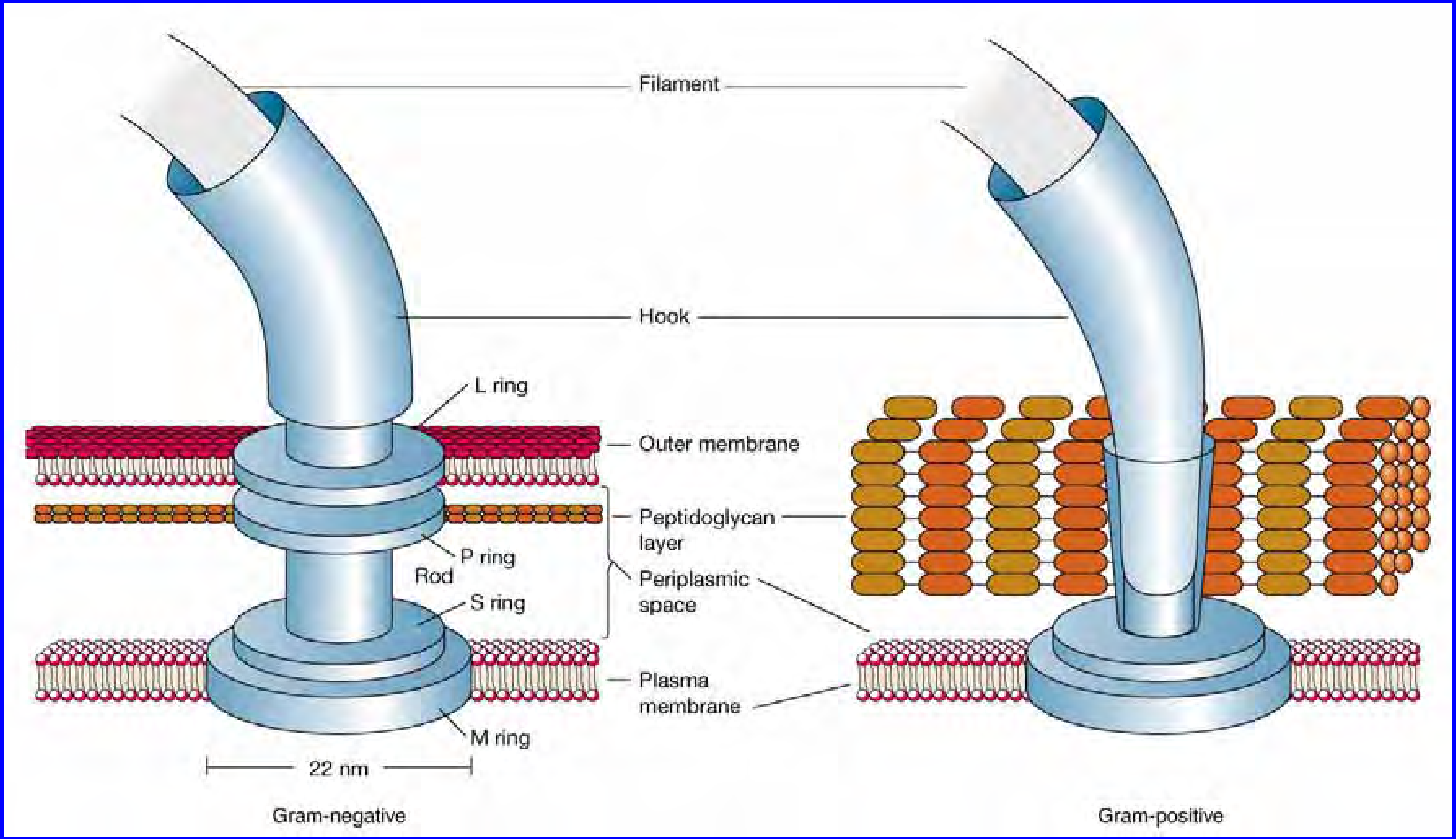

Filament
Hook
L ring
Outer membrane
Peptidoglycan layer
P ring
Rod
S ring
Periplasmic space
Plasma membrane
M ring
22 nm
Gram-negative
Gram-positive

Figure 3.34

The filament

- hollow, rigid cylinder
- composed of the protein flagellin
- some procaryotes have a sheath around filament

The hook and basal body

- **hook**
  - **links filament to basal body**
- **basal body**
  - **series of rings that drive flagellar motor**

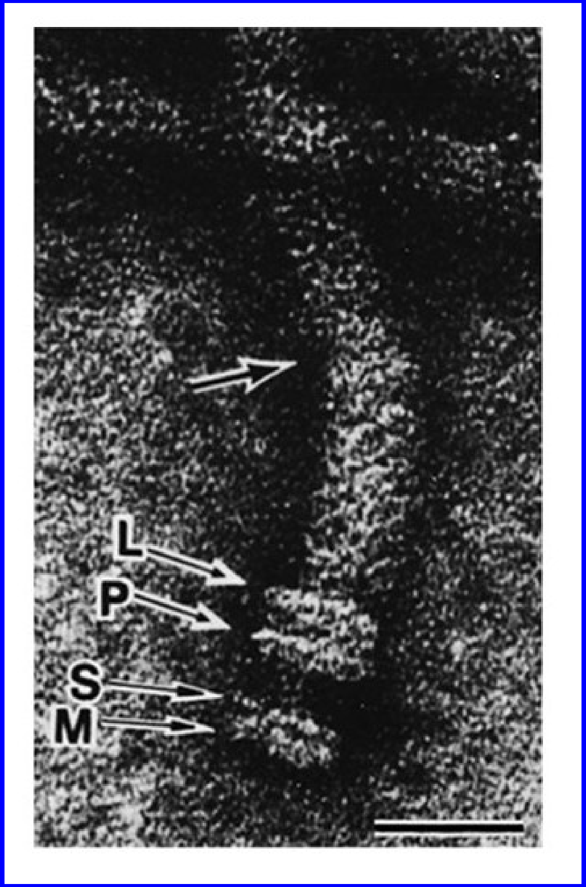


Figure 3.33b

Flagellar Synthesis

- an example of **self-assembly**
- complex process involving many genes and gene products
- new molecules of flagellin are transported through the hollow filament
- growth is from tip, not base

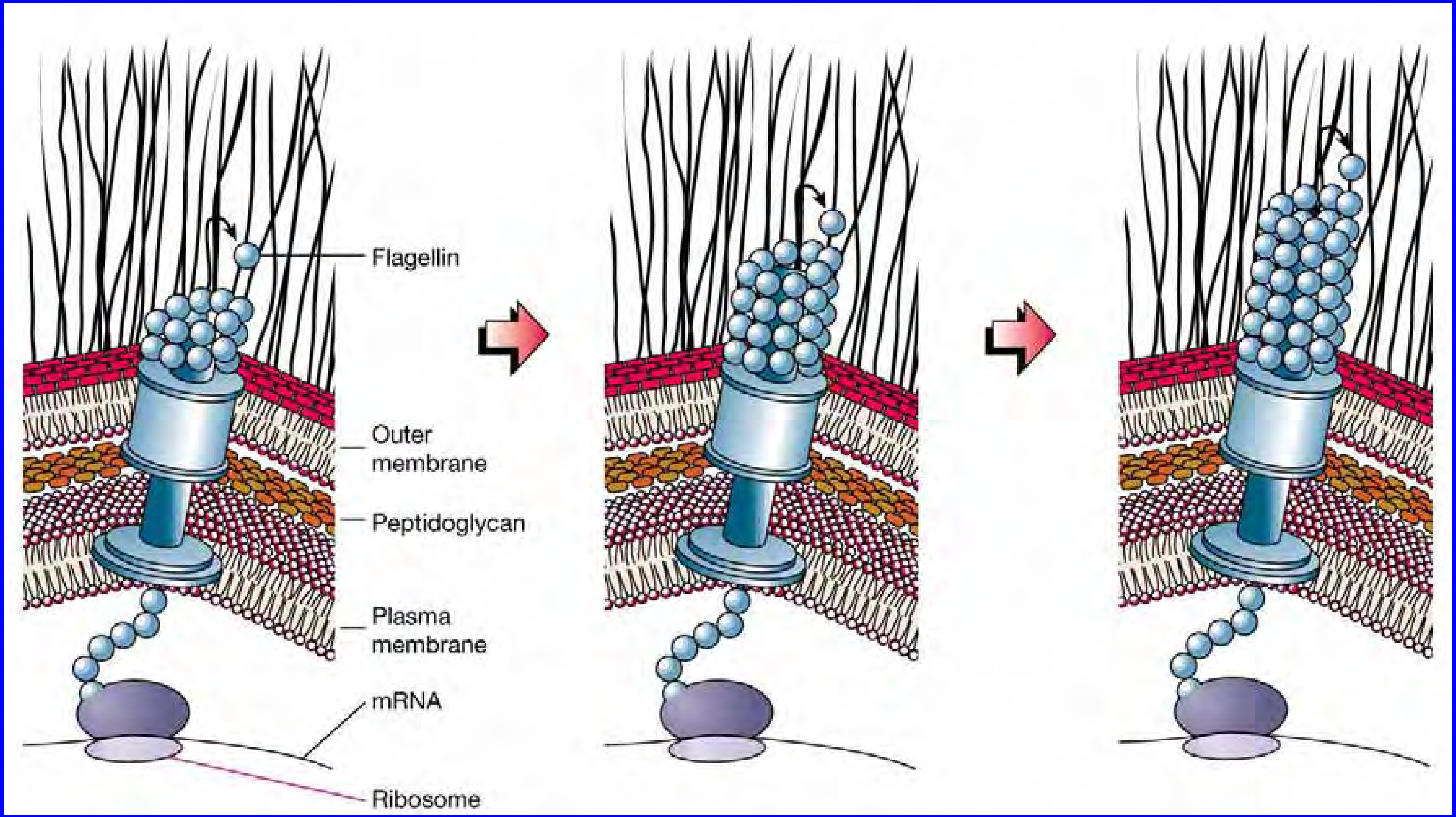

Flagellin
Outer membrane
Peptidoglycan
Plasma membrane
mRNA
Ribosome

Figure 3.35

The Mechanism of Flagellar Movement

- flagellum rotates like a propeller
  - in general, counterclockwise rotation causes forward motion (run)
  - in general, clockwise rotation disrupts run causing a tumble (twiddle)

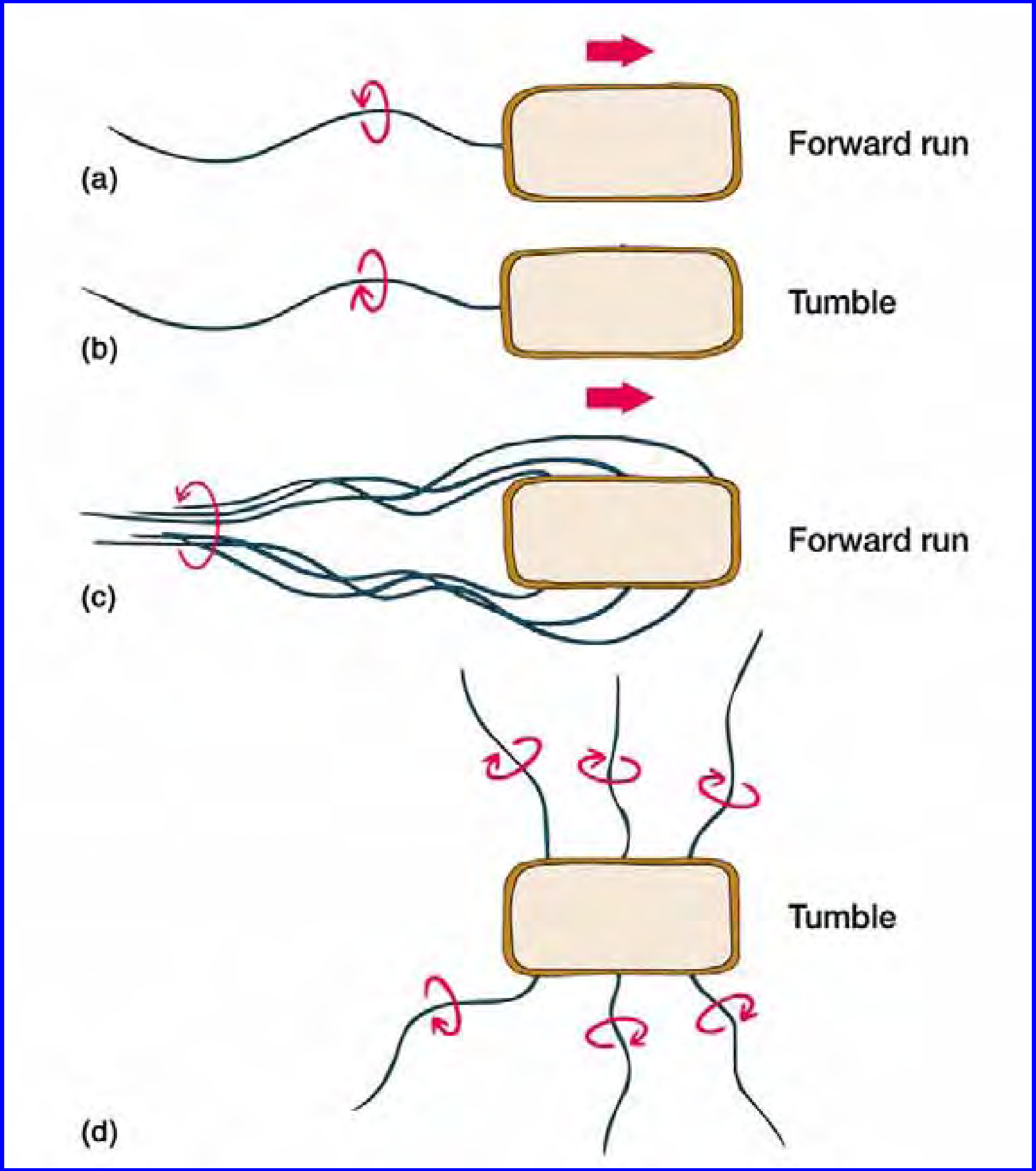


Figure 3.36

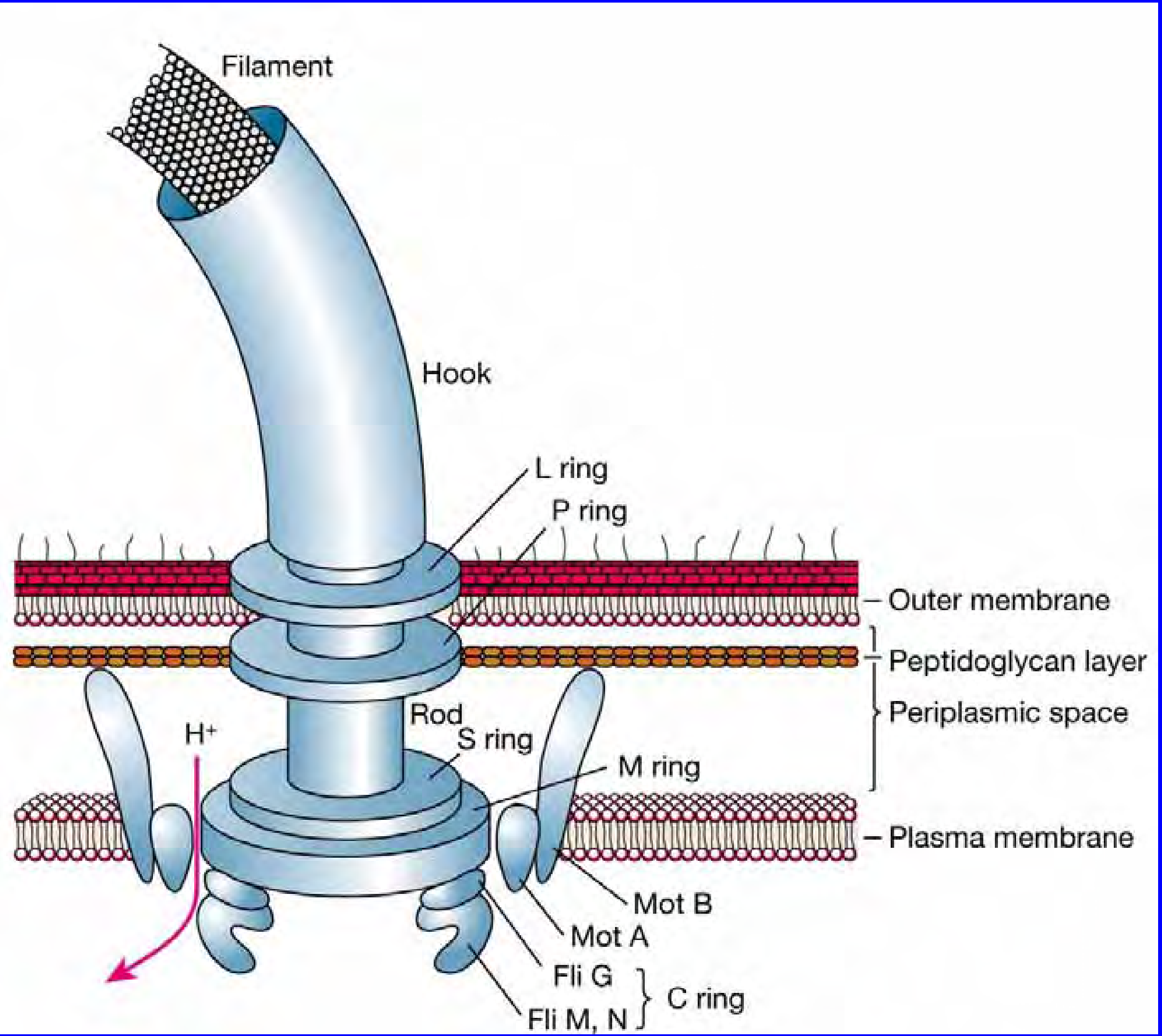

Filament
Hook
L ring
P ring
Outer membrane
Peptidoglycan layer
Periplasmic space
Rod
S ring
M ring
H+
Plasma membrane
Mot B
Mot A
Fli G
Fli M, N
C ring

Figure 3.37

Other types of motility

- spirochetes
  - axial filaments cause flexing and spinning movement
- gliding motility
  - cells coast along solid surfaces
  - no visible motility structure has been identified

Chemotaxis

- movement towards a chemical attractant or away from a chemical repellant
- concentrations of chemoattractants and chemorepellants detected by **chemoreceptors** on surfaces of cells

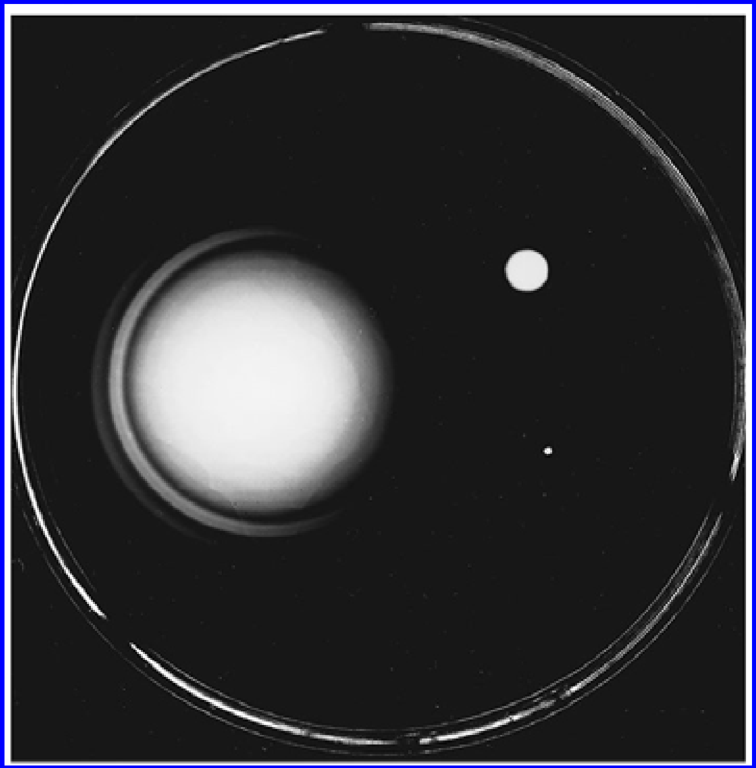


Figure 3.38

Figure 3.39

Travel towards attractant

- caused by lowering the frequency of tumbles
- biased random walk

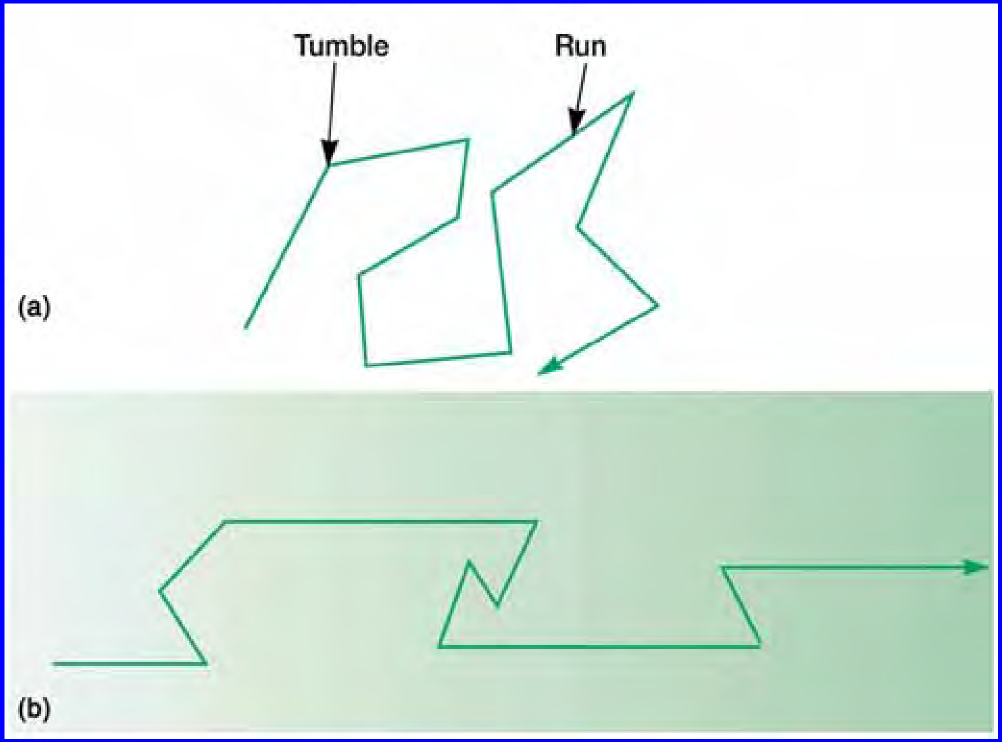


Figure 3.40

Travel away from repellant

- involves similar but opposite responses

Mechanism of chemotaxis

- complex but rapid
  - responses occur in less than 20 milliseconds
- involves conformational changes in proteins
- also involves methylation or phosphorylation of proteins

The Bacterial Endospore

- formed by some bacteria
- dormant
- resistant to numerous environmental conditions
  - heat
  - radiation
  - chemicals
  - desiccation

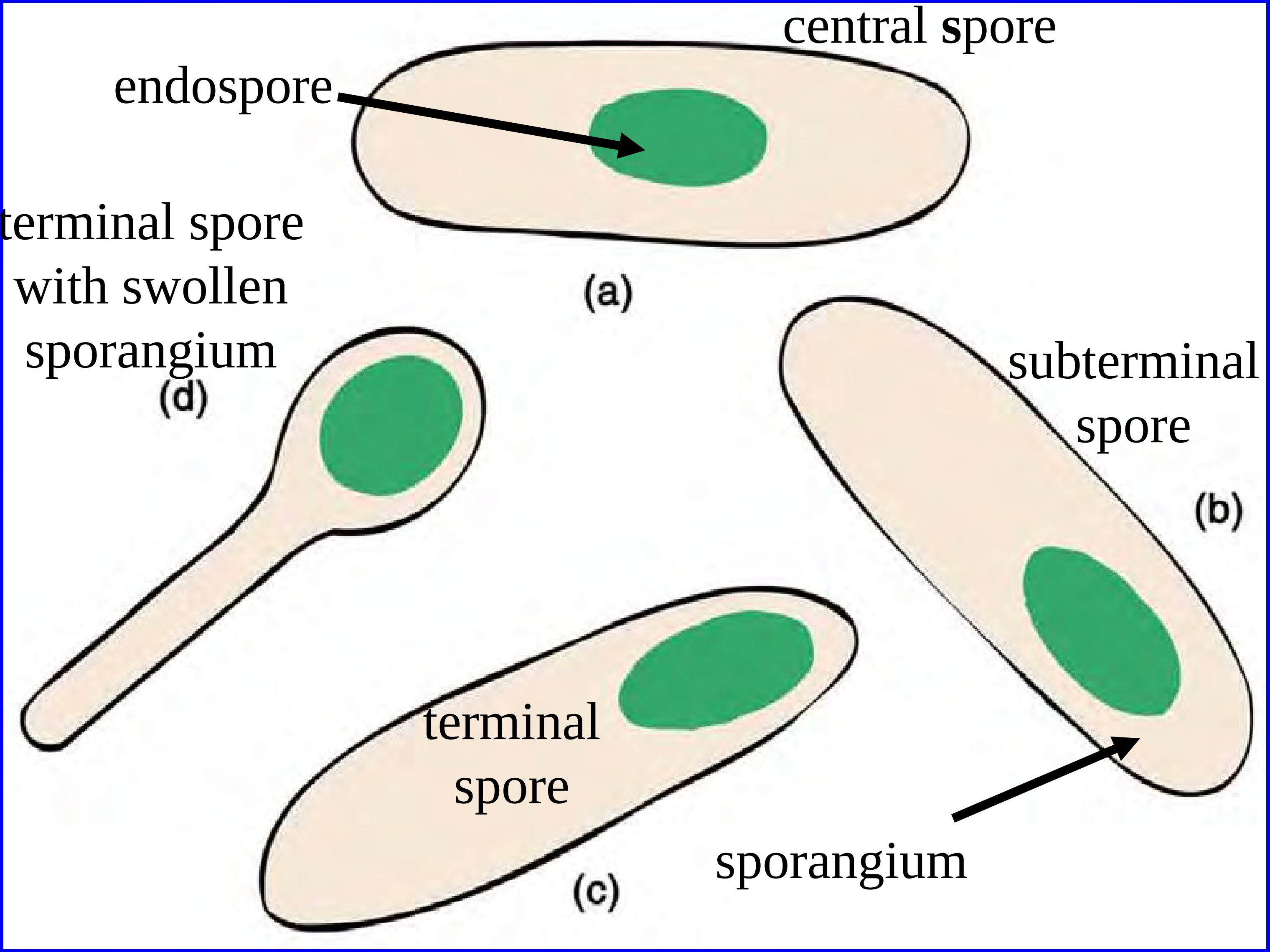

central spore
endospore
terminal spore
with swollen
sporangium
(d)
(a)
subterminal
spore
(b)
terminal
spore
sporangium
(c)

Figure 3.40

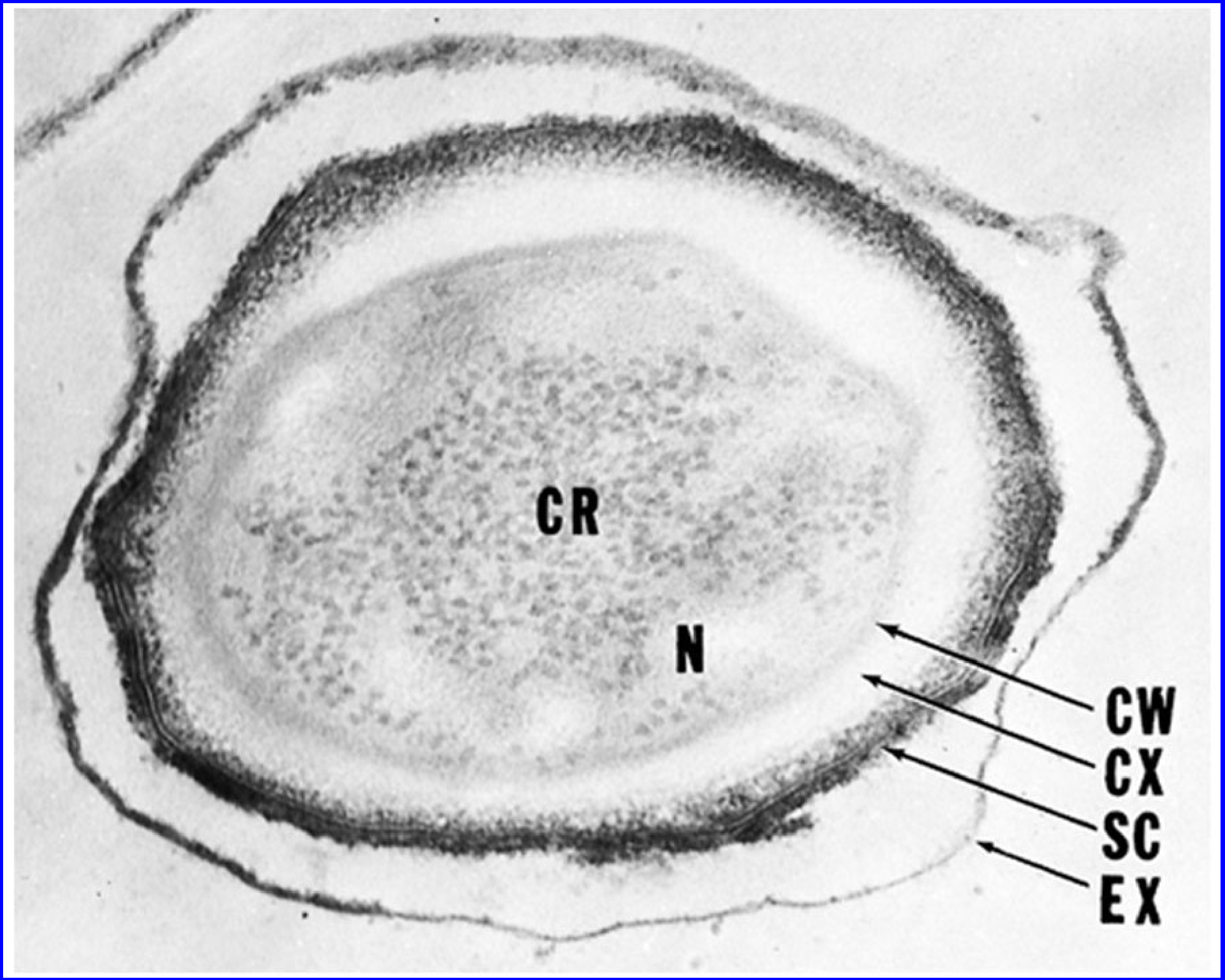


Figure 3.42

What makes an endospore so resistant?

- calcium (complexed with dipicolinic acid)
- acid-soluble, DNA-binding proteins
- dehydrated core
- spore coat
- DNA repair enzymes

Sporogenesis

- **normally commences when growth ceases because of lack of nutrients**
- **complex multistage process**

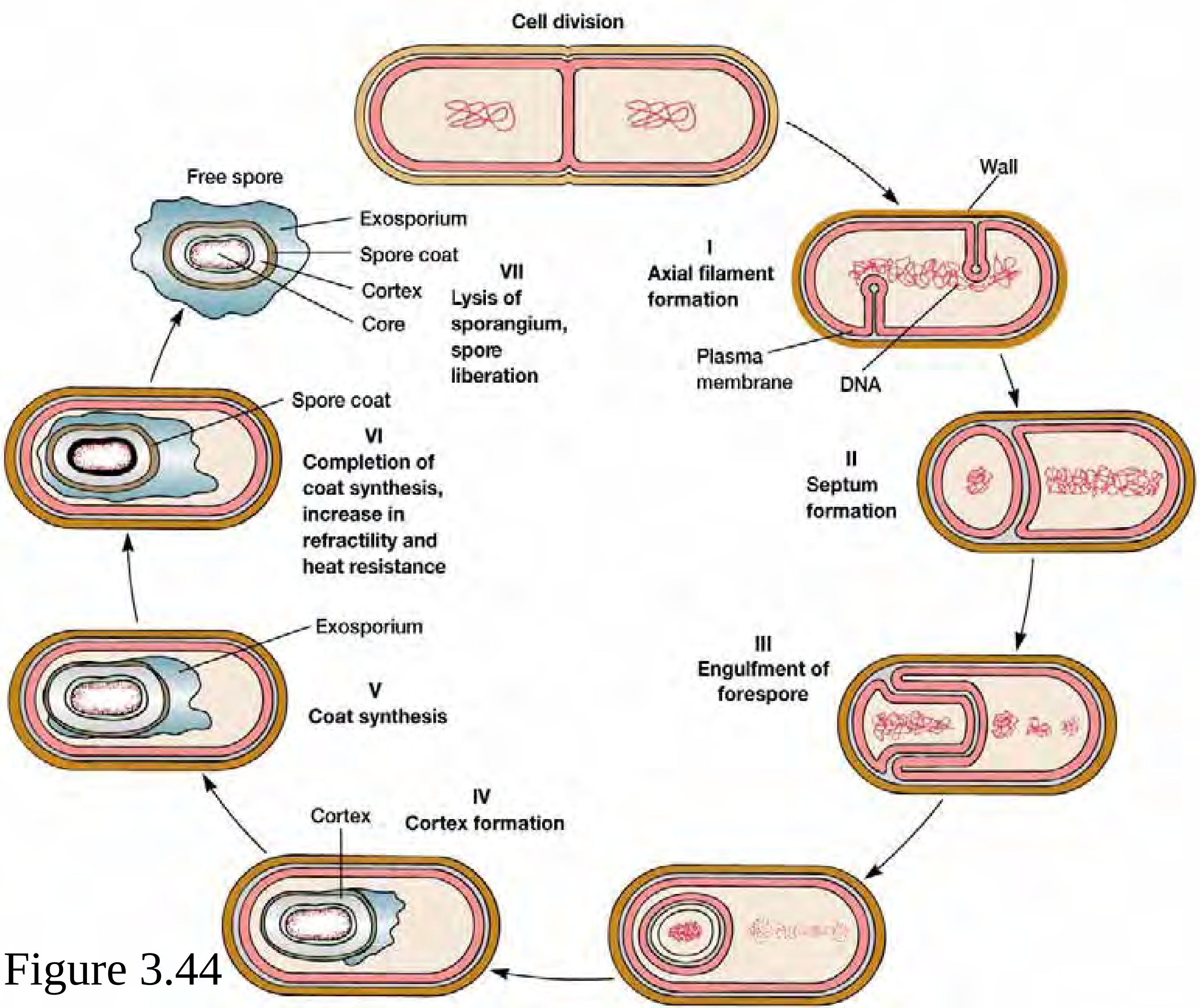

Cell division
Wall
I
Axial filament formation
Plasma membrane
DNA
II
Septum formation
III
Engulfment of forespore
IV
Cortex formation
Cortex
V
Coat synthesis
Exosporium
VI
Completion of coat synthesis, increase in refractility and heat resistance
Spore coat
VII
Lysis of sporangium, spore liberation
Free spore
Exosporium
Spore coat
Cortex
Core

Figure 3.44

Transformation of endospore into vegetative cell

- **complex, multistage process**

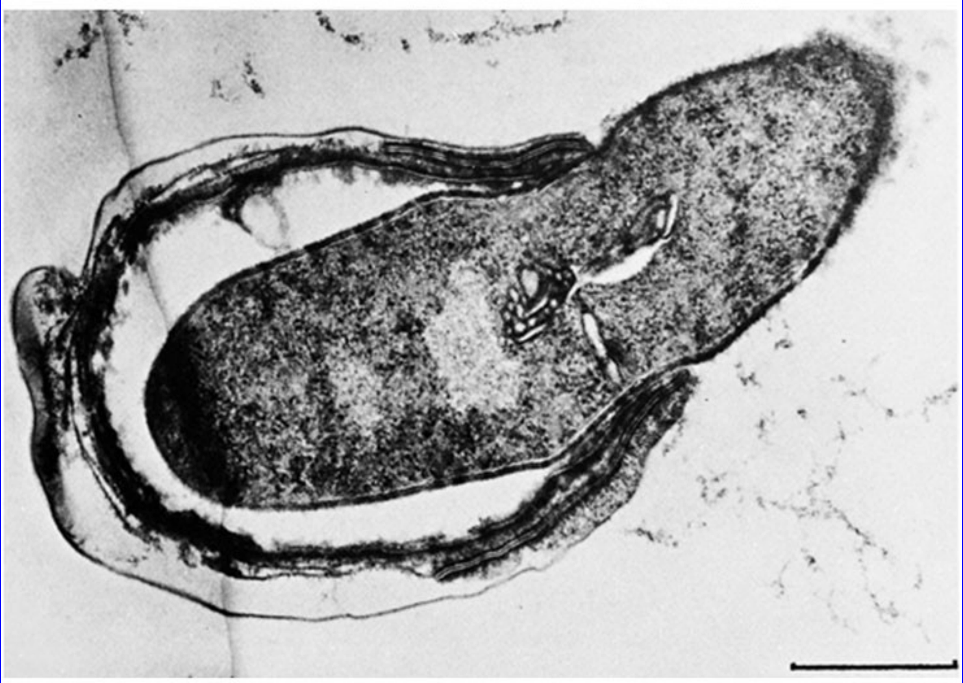


Figure 3.45

Stages in transformation

- activation
  - prepares spores for germination
  - often results from treatments like heating
- germination
  - spore swelling
  - rupture of absorption of spore coat
  - loss of resistance
  - increased metabolic activity
- outgrowth
  - emergence of vegetative cell