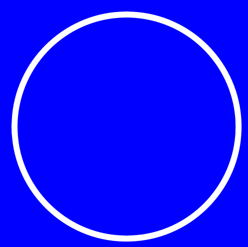
Chapter 3

The Prokaryotic Cell Structure and Function

Does Size Matter?

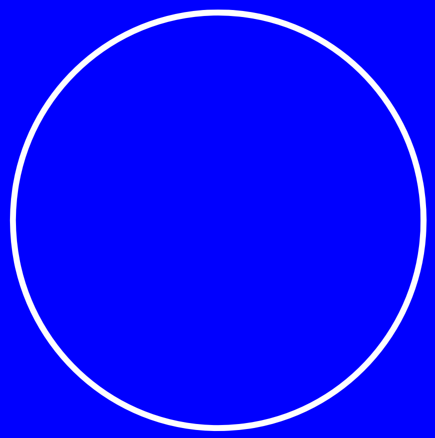
for a sphere: surface area = $4\pi r^2$; volume = $4/3\pi r^3$

if r = 1 µm; then surface area = 12.6 and vol. = 4.2



surface area/volume = 3

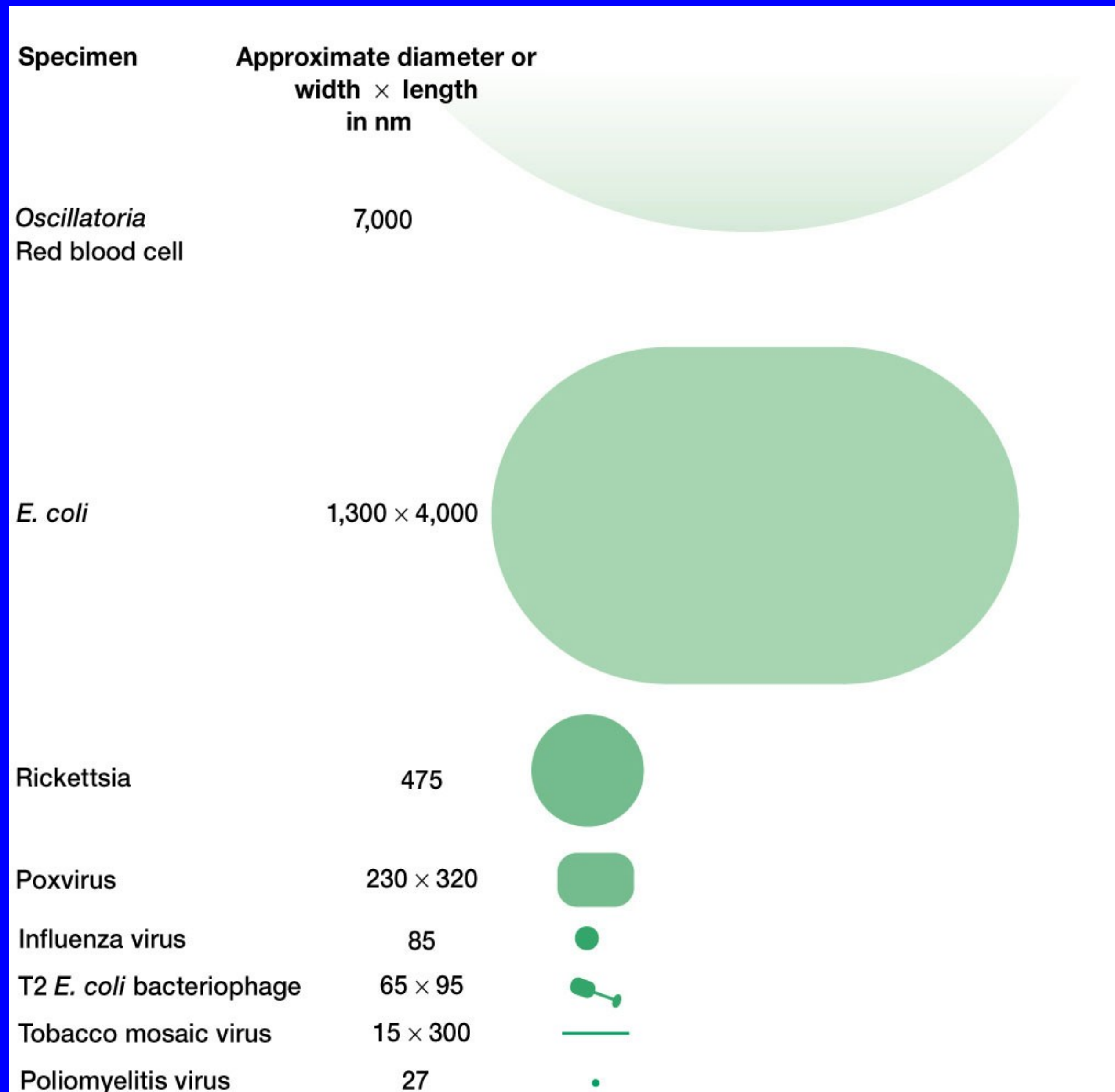
if r = 2 µm; then surface area = 50.3 and vol. = 33.5



surface area/volume = 1.5

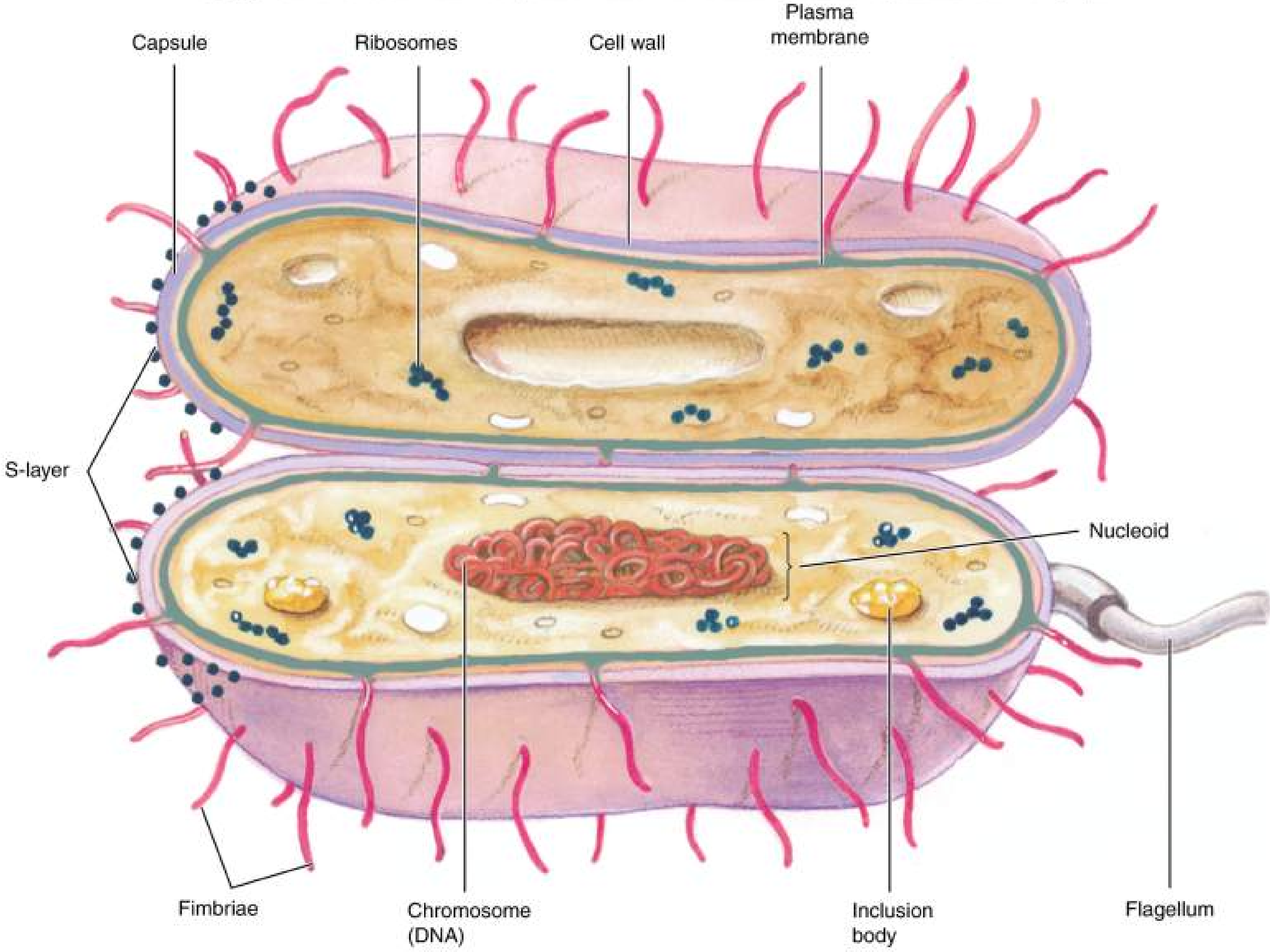
- largest – ≥50 µm in diameter

- smallest – 0.3 µm in diameter



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

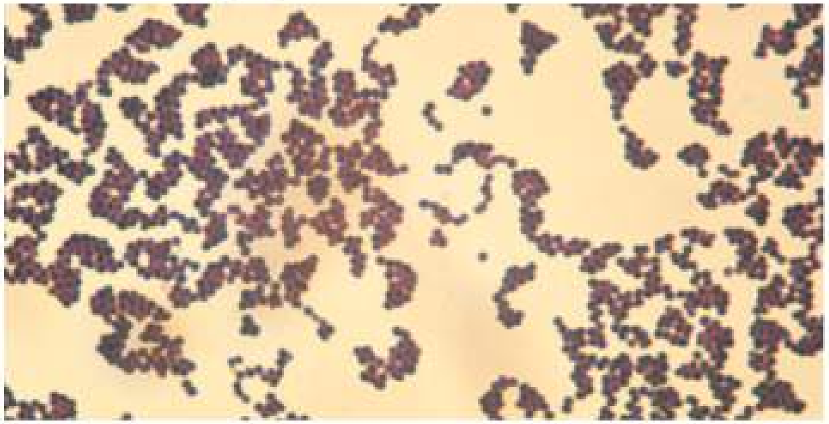

Capsule
Ribosomes
Cell wall
Plasma membrane
S-layer
Nucleoid
Fimbriae
Chromosome (DNA)
Inclusion body
Flagellum

Size, Shape, and Arrangement

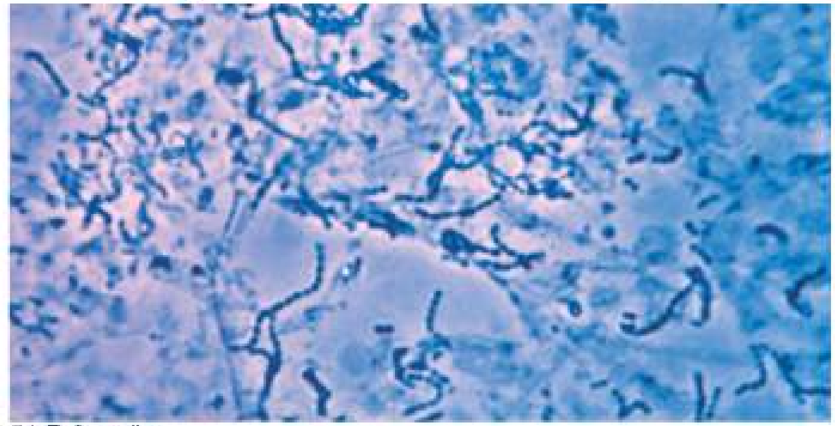
- **cocci (s., coccus) – spheres**
  - **diplococci (s., diplococcus) – pairs**
  - **streptococci – chains**
  - **staphylococci – grape-like clusters**
  - **tetrads – 4 cocci in a square**
  - **sarcinae – cubic configuration of 8 cocci**

Size, Shape, and Arrangement

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

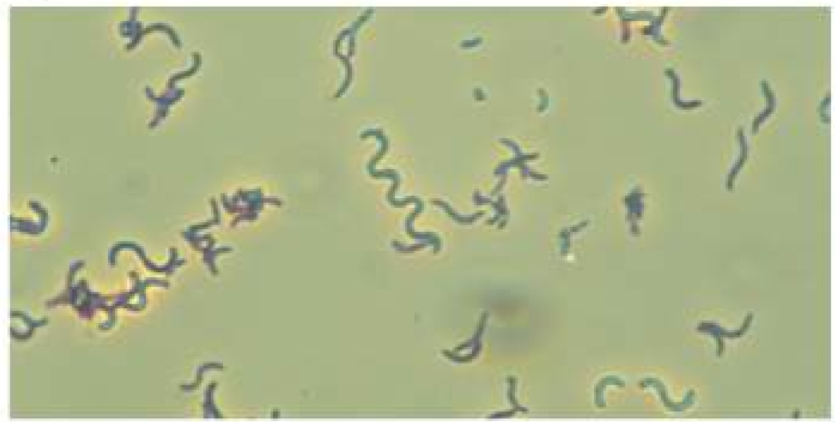


(a) *S. aureus*

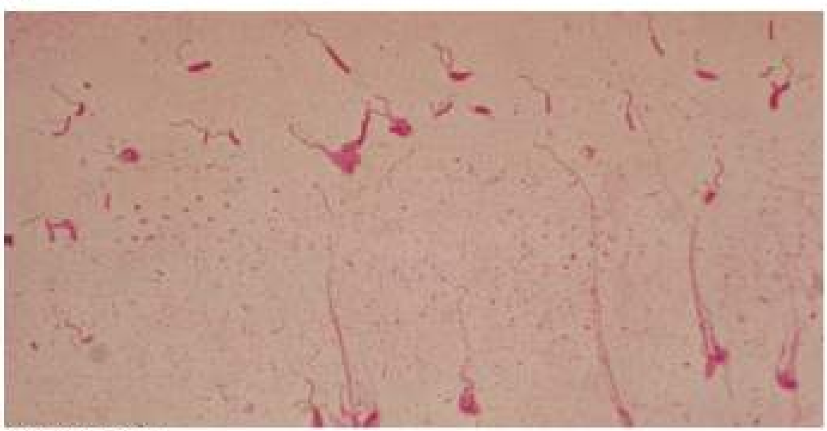


(b) *E. faecalis*

(c) *B. megaterium*



(d) *R. rubrum*

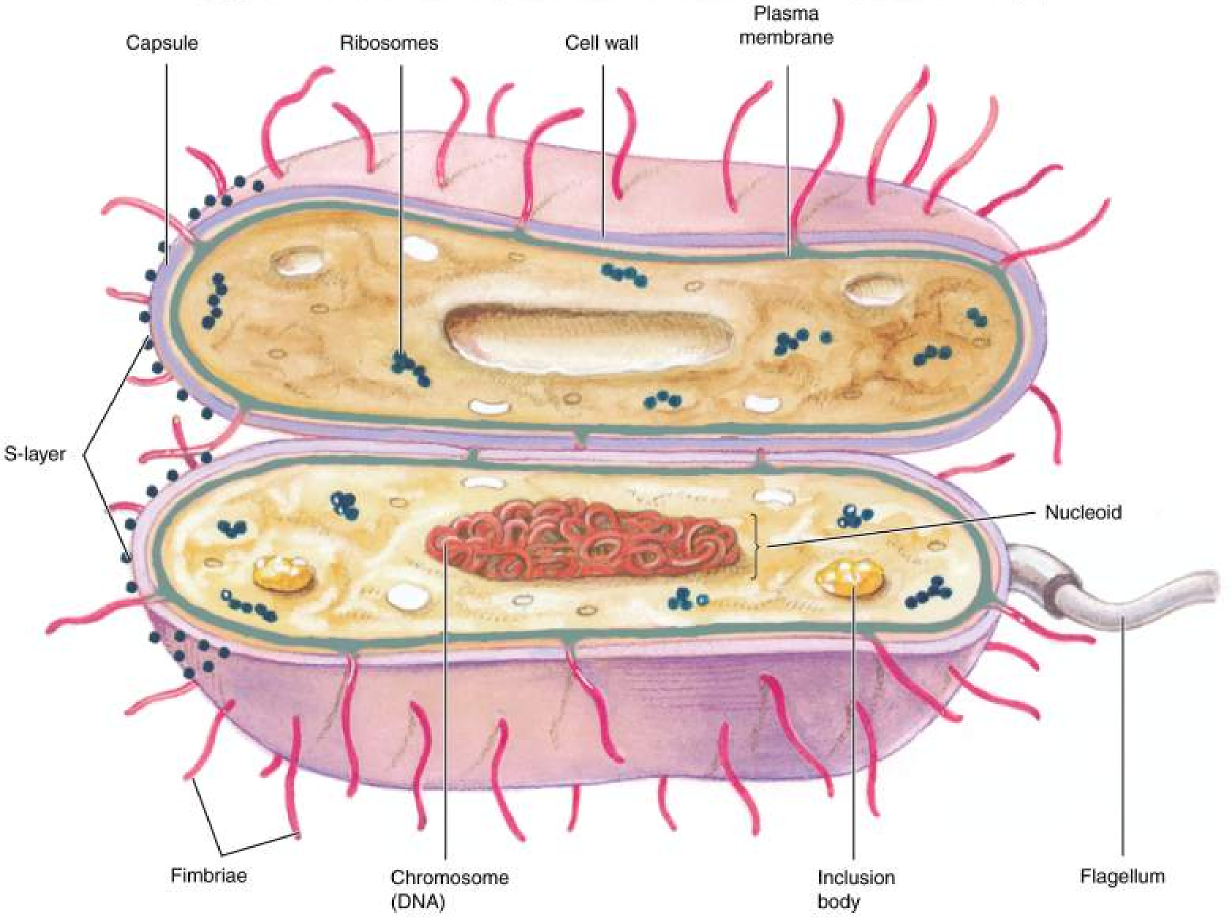


(e) *V. cholerae*

Size, Shape, and Arrangement

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

Flagella and Motility



Motile Cells

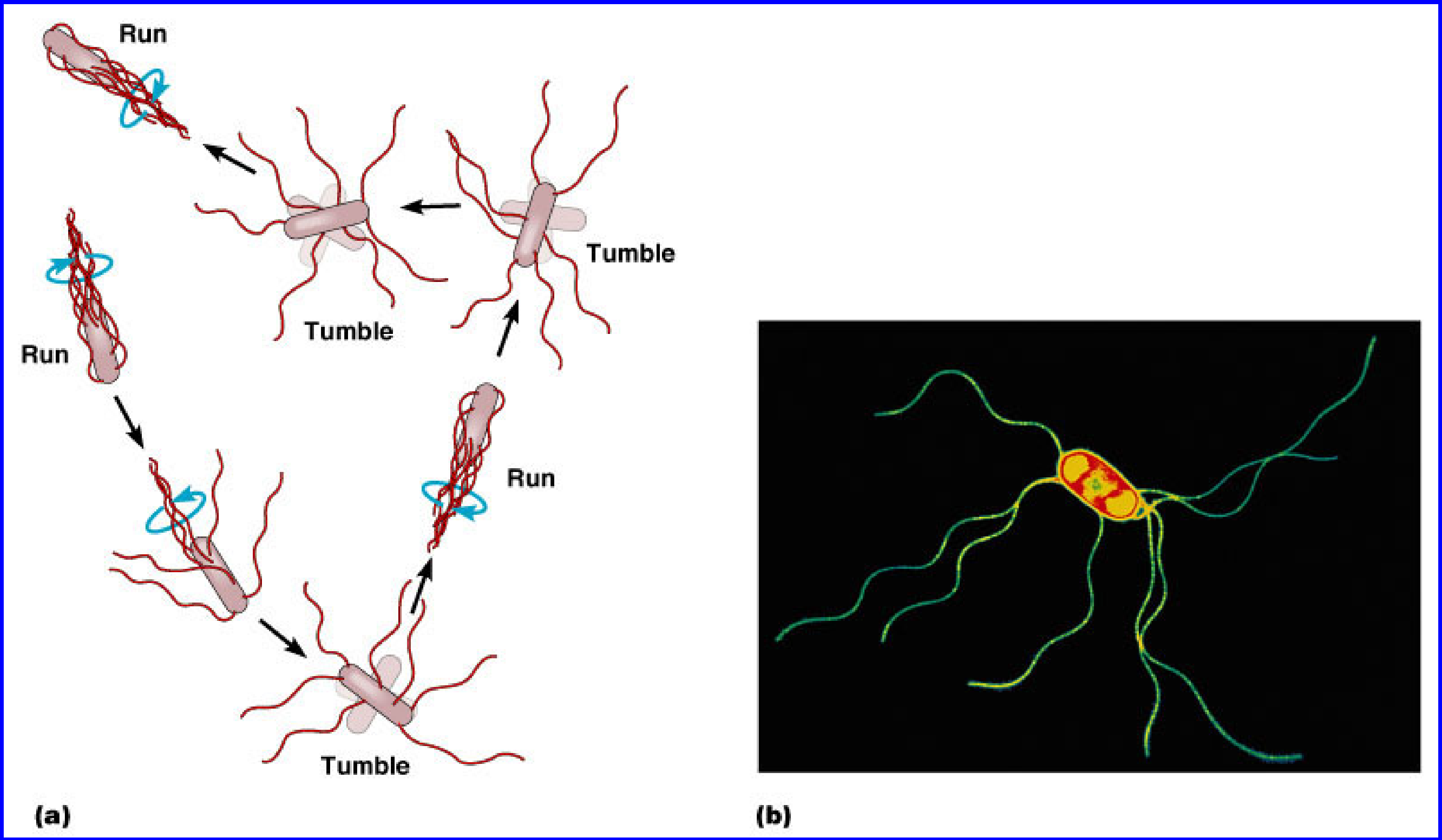


Figure 4.9

The filament

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

Flagellar Ultrastructure

- 3 parts
  - filament
  - basal body
  - hook

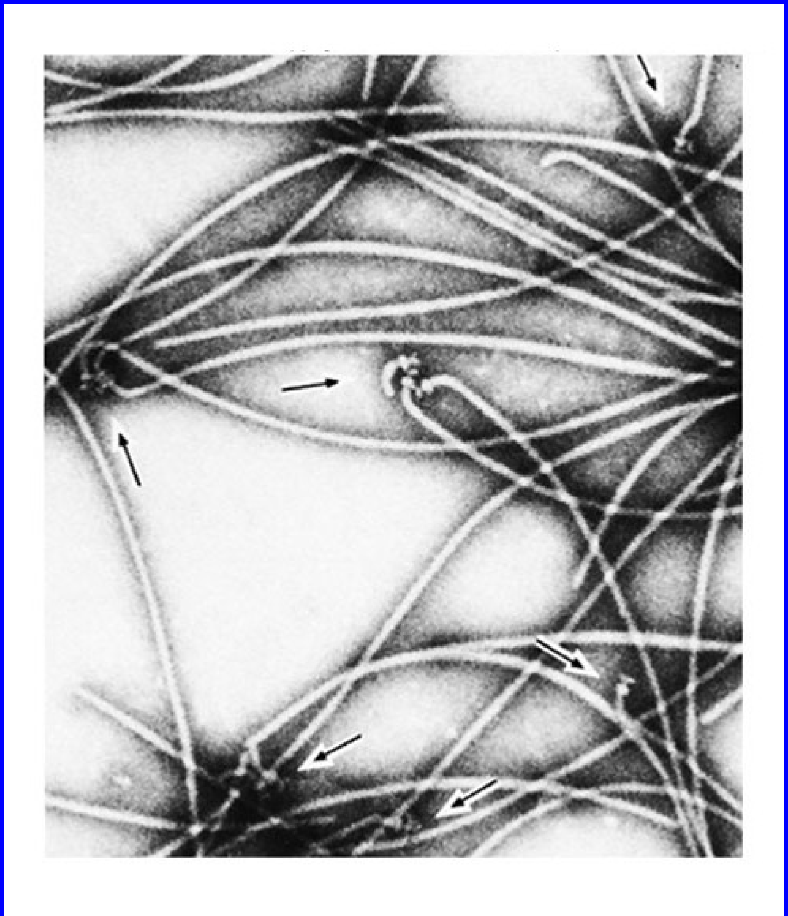


Figure 3.33a

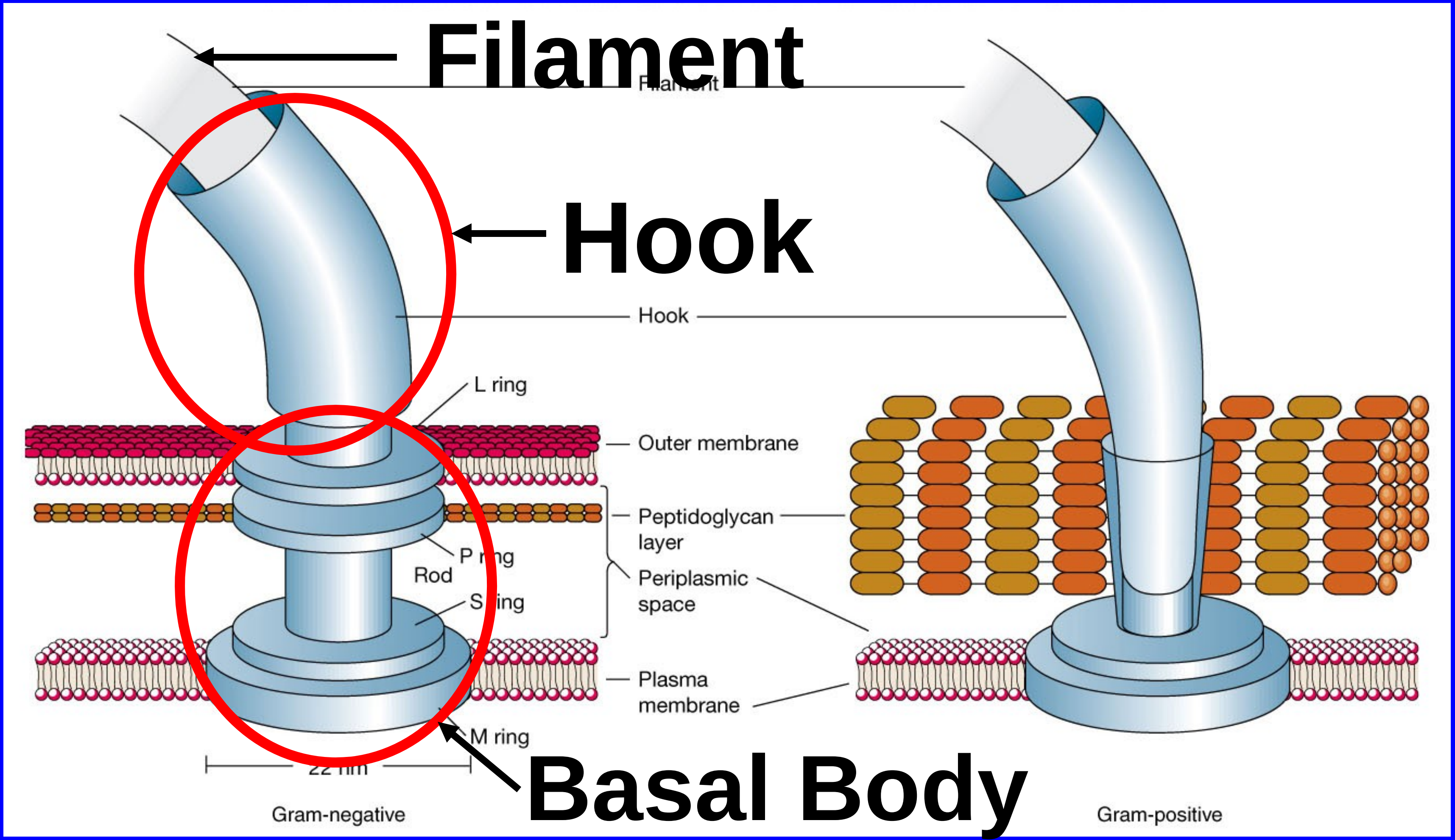

Filament
Hook
Basal Body
Filament
Hook
L ring
Outer membrane
Peptidoglycan layer
Periplasmic space
Plasma membrane
Rod
M ring
Gram-negative
Gram-positive

Figure 3.34

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

The hook and basal body

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

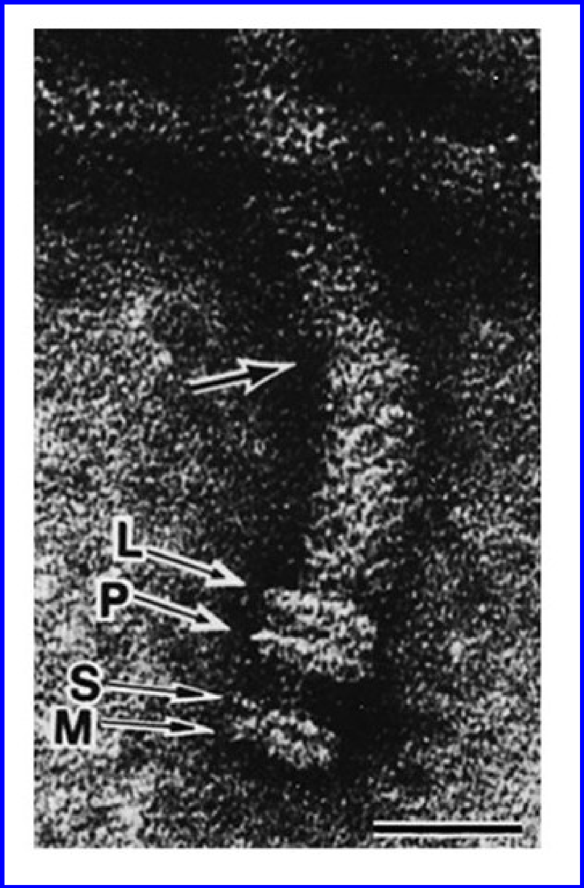
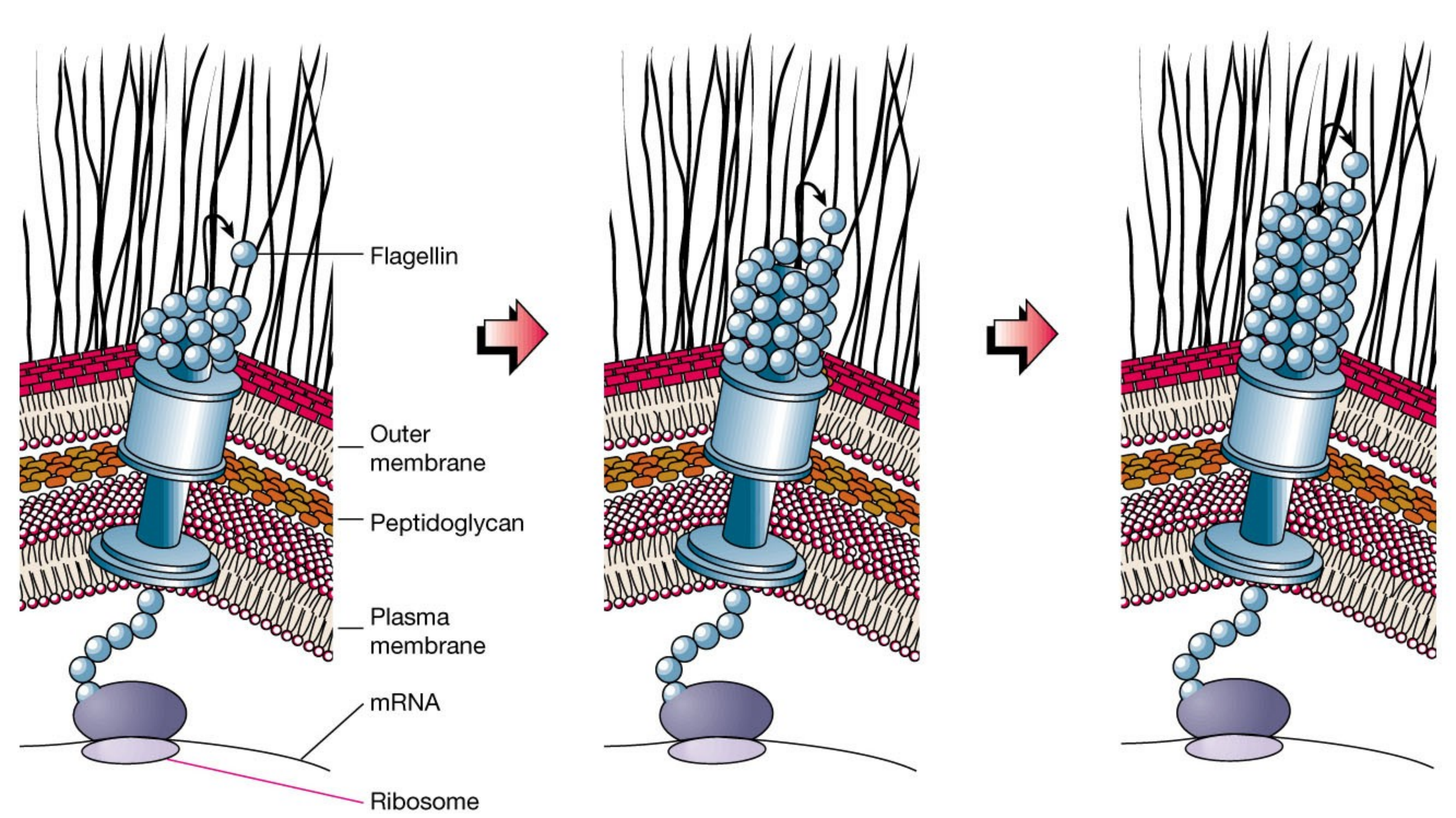


Figure 3.33b



Flagellin
Outer membrane
Peptidoglycan
Plasma membrane
mRNA
Ribosome

Figure 3.35

Chemotaxis

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

Travel towards attractant

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

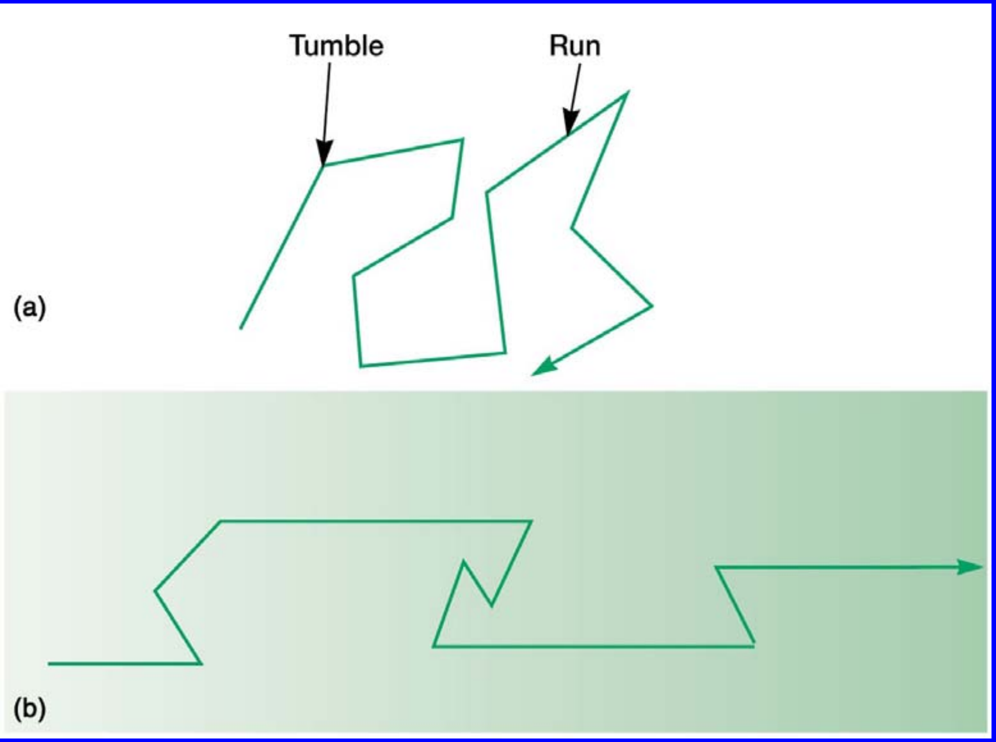
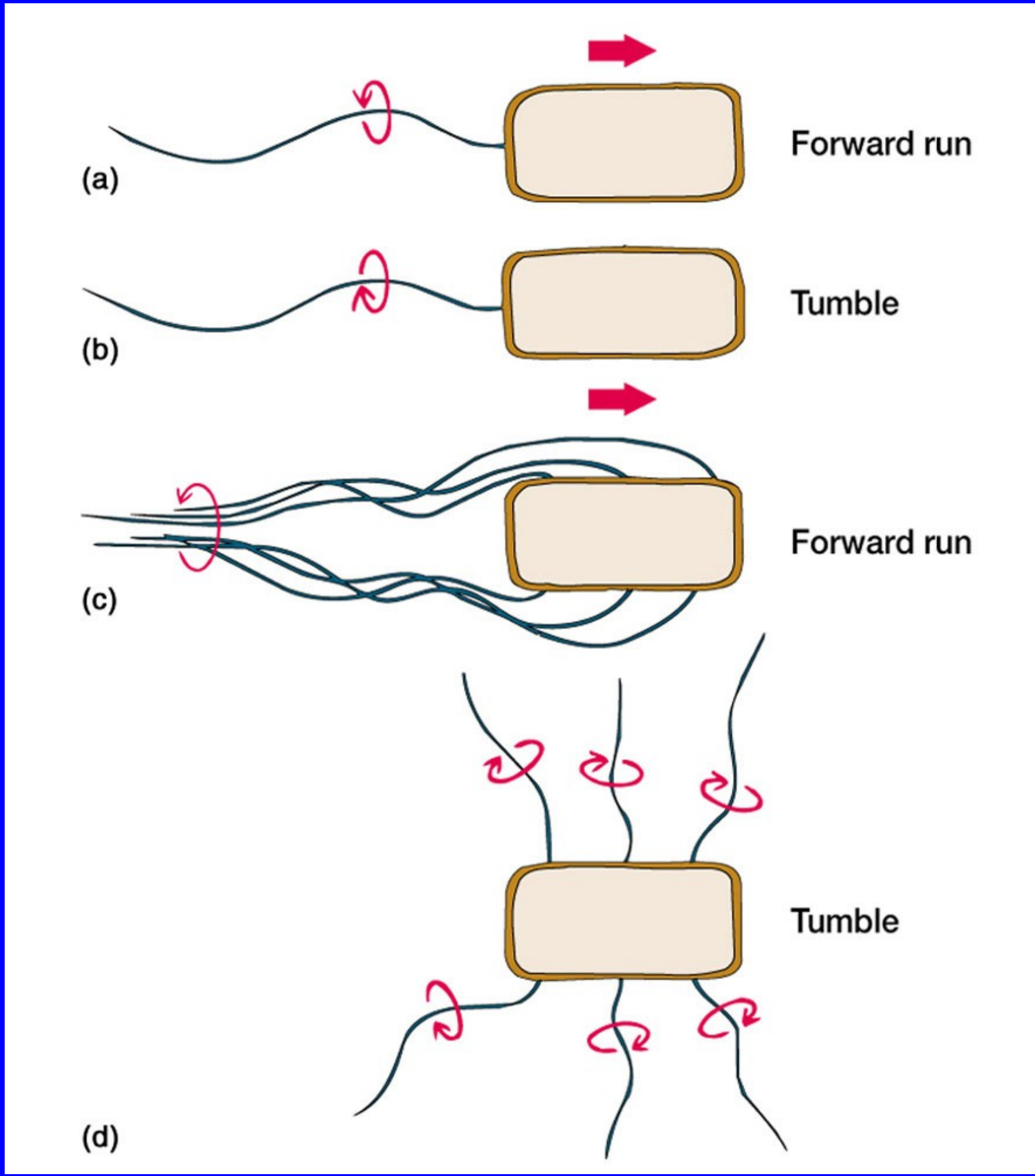


Figure 3.40

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**

- Flagella can spin over 60,000 rpm
- Cells can travel up to 90µm/sec and swim up to 100 cell lengths/sec (fast man runs at 5 lengths/sec)



The Mechanism of Flagellar Movement

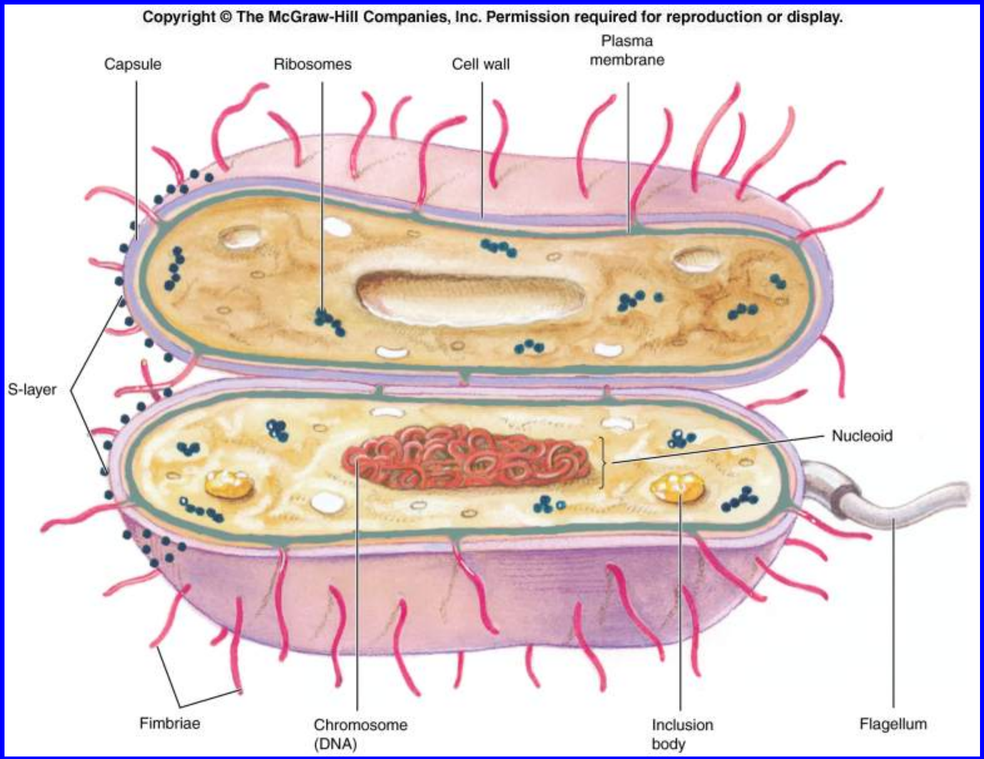
- flagellum rotates like a propeller
  - in general, counterclockwise rotation causes forward motion (**run**)
  - in general, clockwise rotation disrupts run causing a **tumble** (**twiddle**)

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**

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**
- **region of energy metabolism**

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

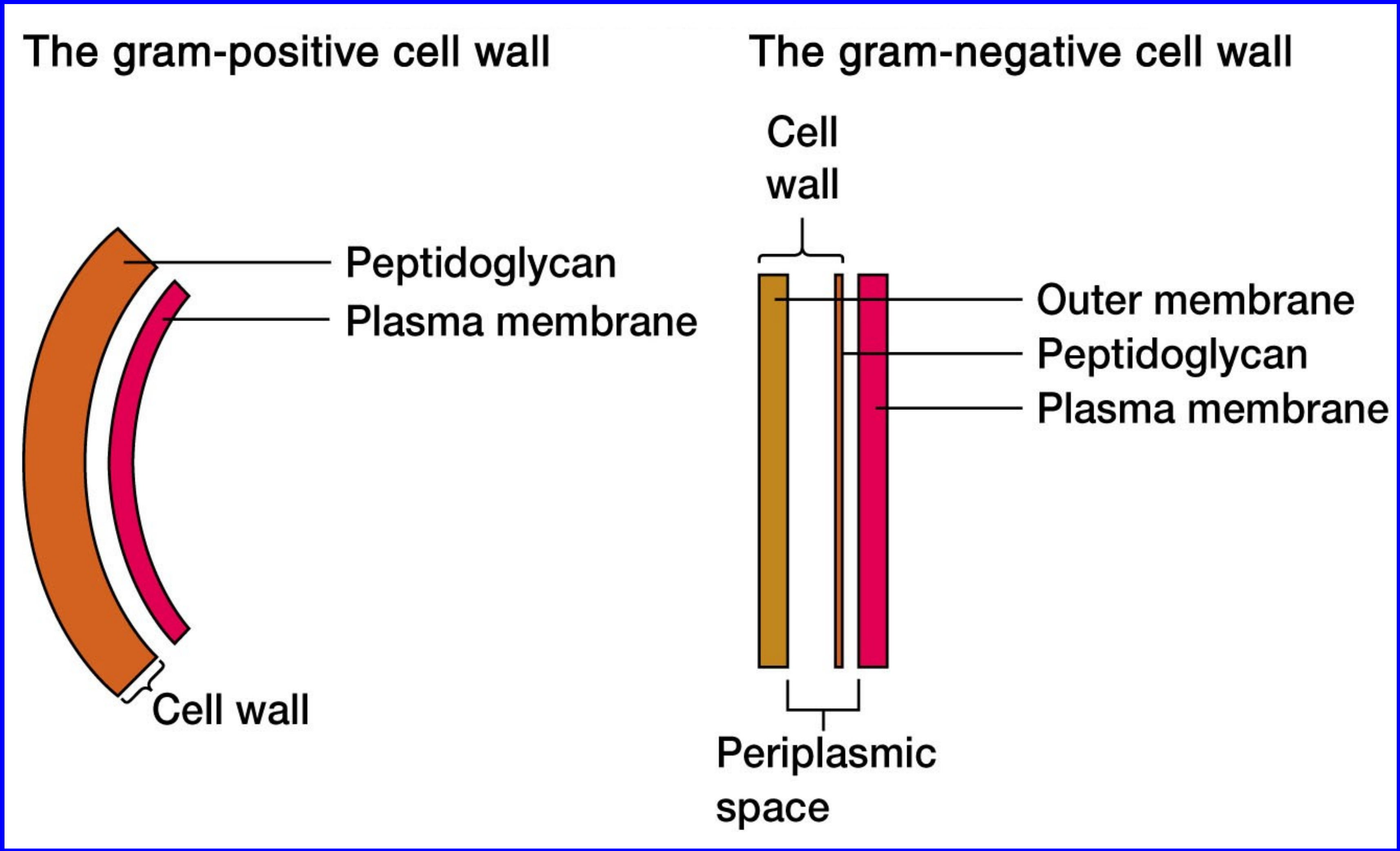

The gram-positive cell wall
Peptidoglycan
Plasma membrane
Cell wall
The gram-negative cell wall
Cell wall
Outer membrane
Peptidoglycan
Plasma membrane
Periplasmic space

Figure 3.15

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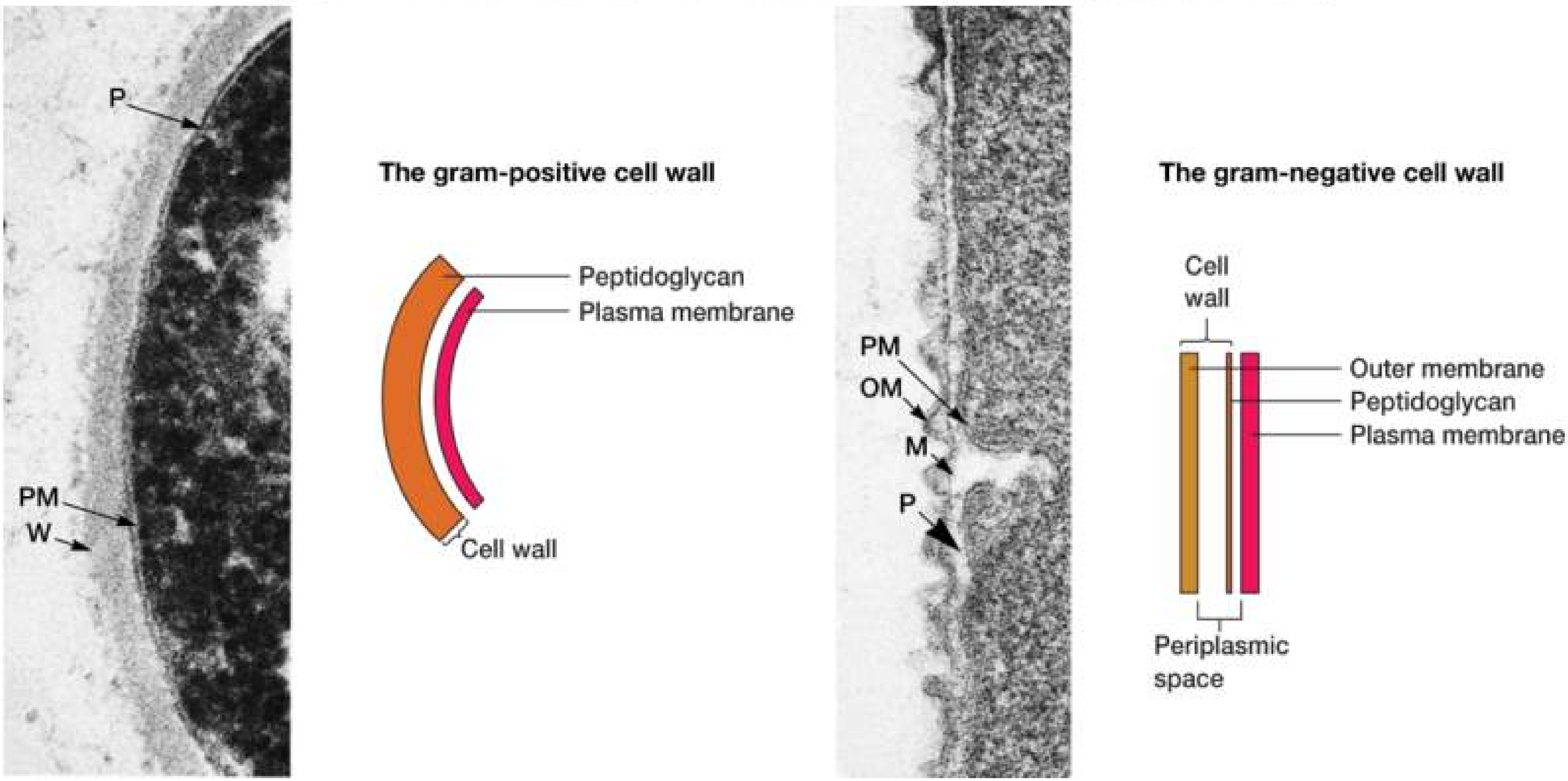


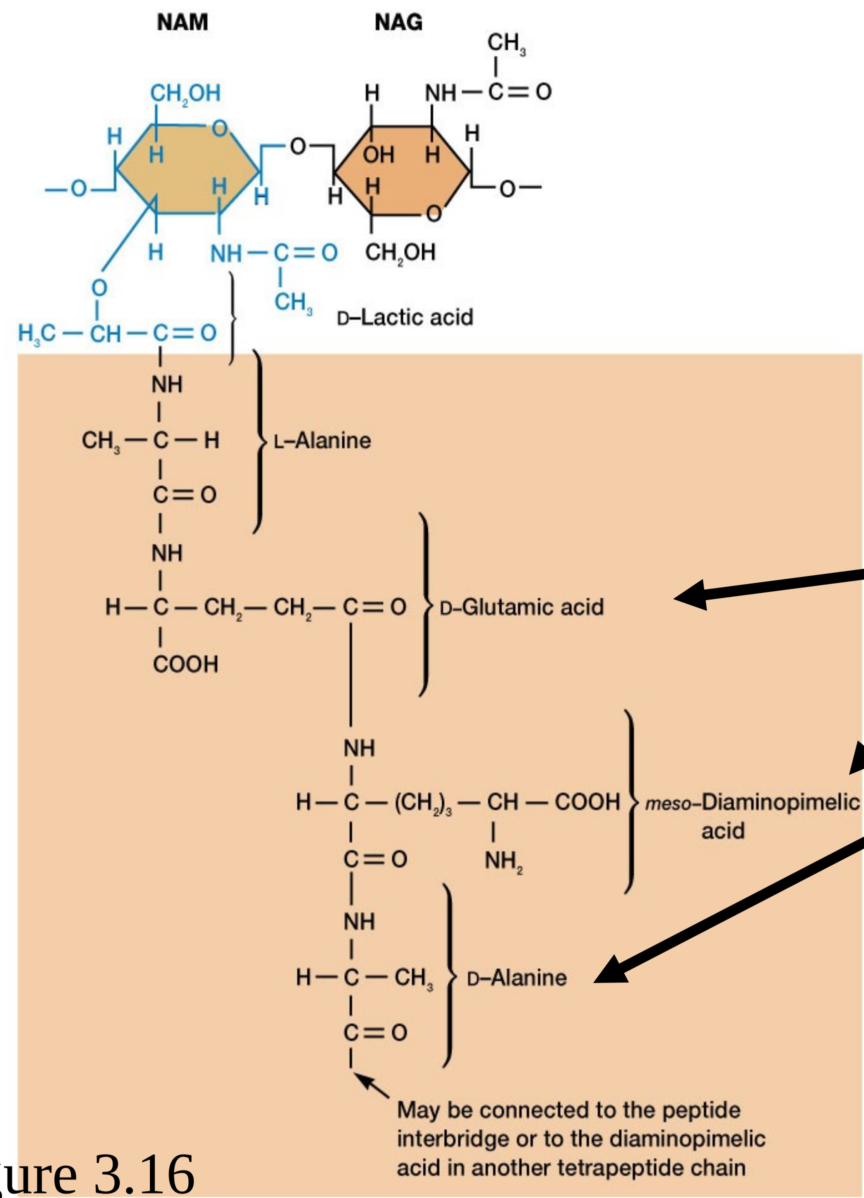
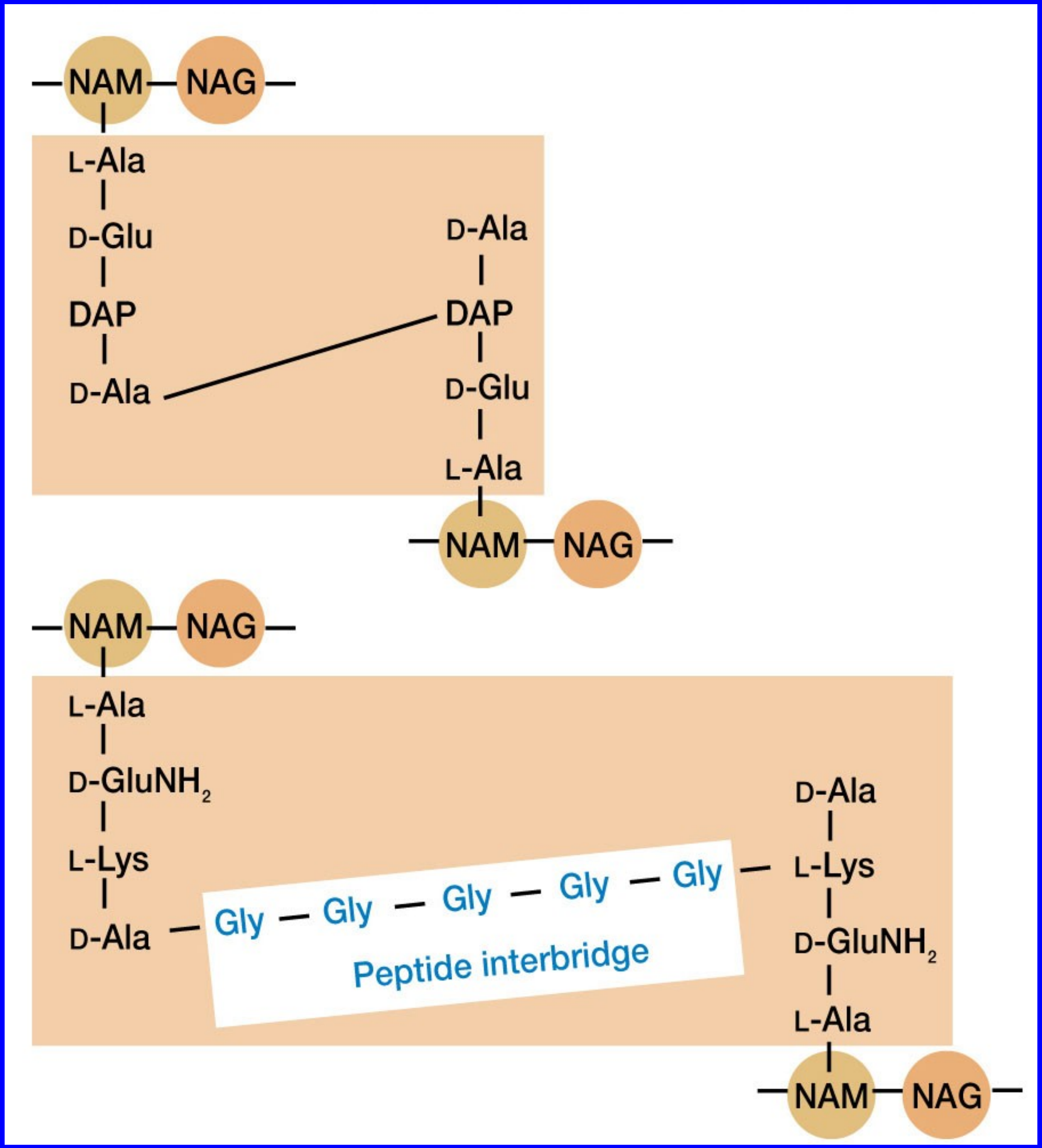


Figure 3.16

some amino acids are not observed in proteins

Gram -

Gram +


NAM
NAG
L-Ala
D-Glu
DAP
D-Ala
D-Ala
DAP
D-Glu
L-Ala
NAM
NAG
NAM
NAG
L-Ala
D-GluNH2
L-Lys
D-Ala
Gly — Gly — Gly — Gly — Gly
Peptide interbridge
D-Ala
L-Lys
D-GluNH2
L-Ala
NAM
NAG

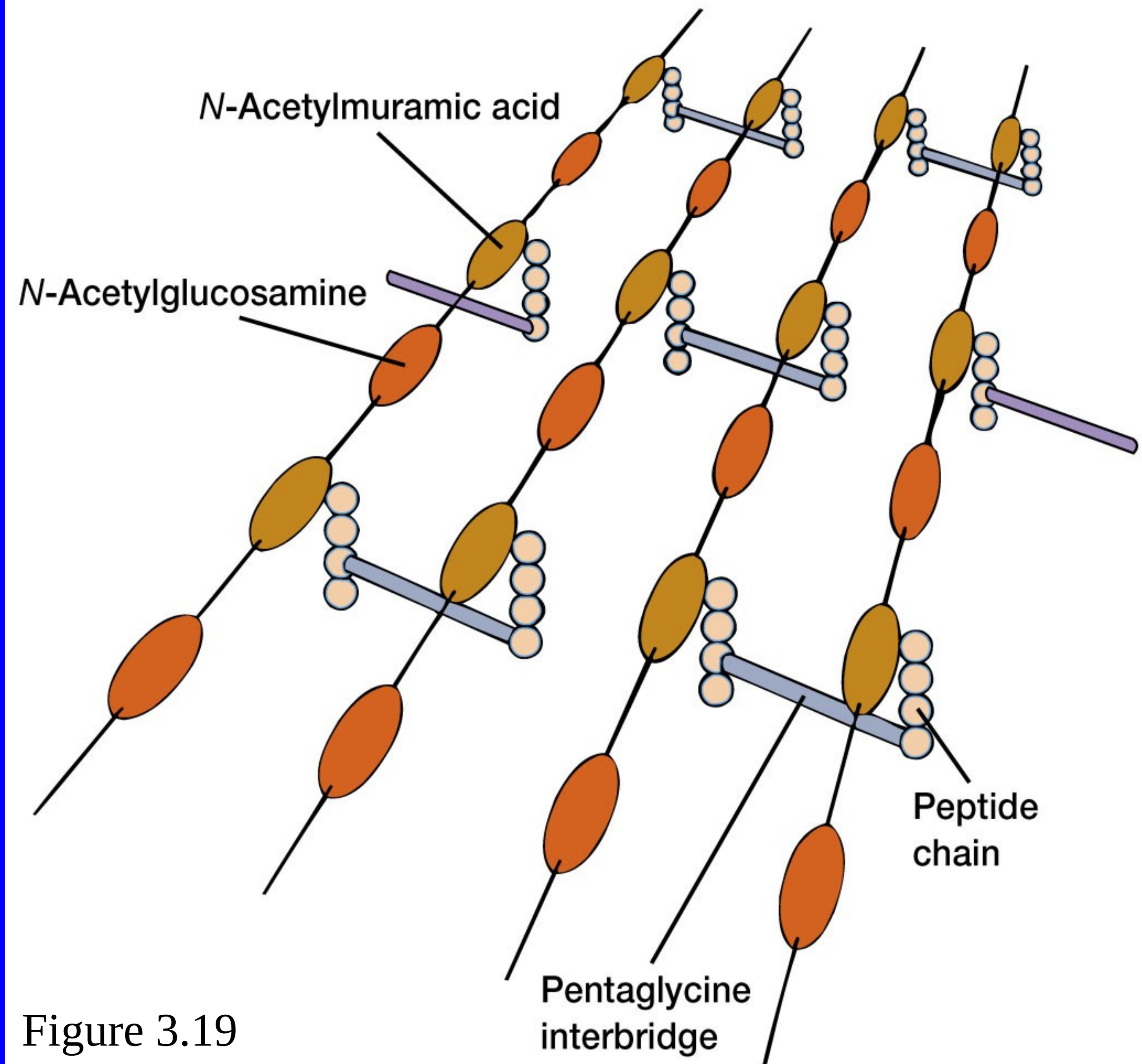

N-Acetylmuramic acid
N-Acetylglucosamine
Peptide chain
Pentaglycine interbridge

Figure 3.19

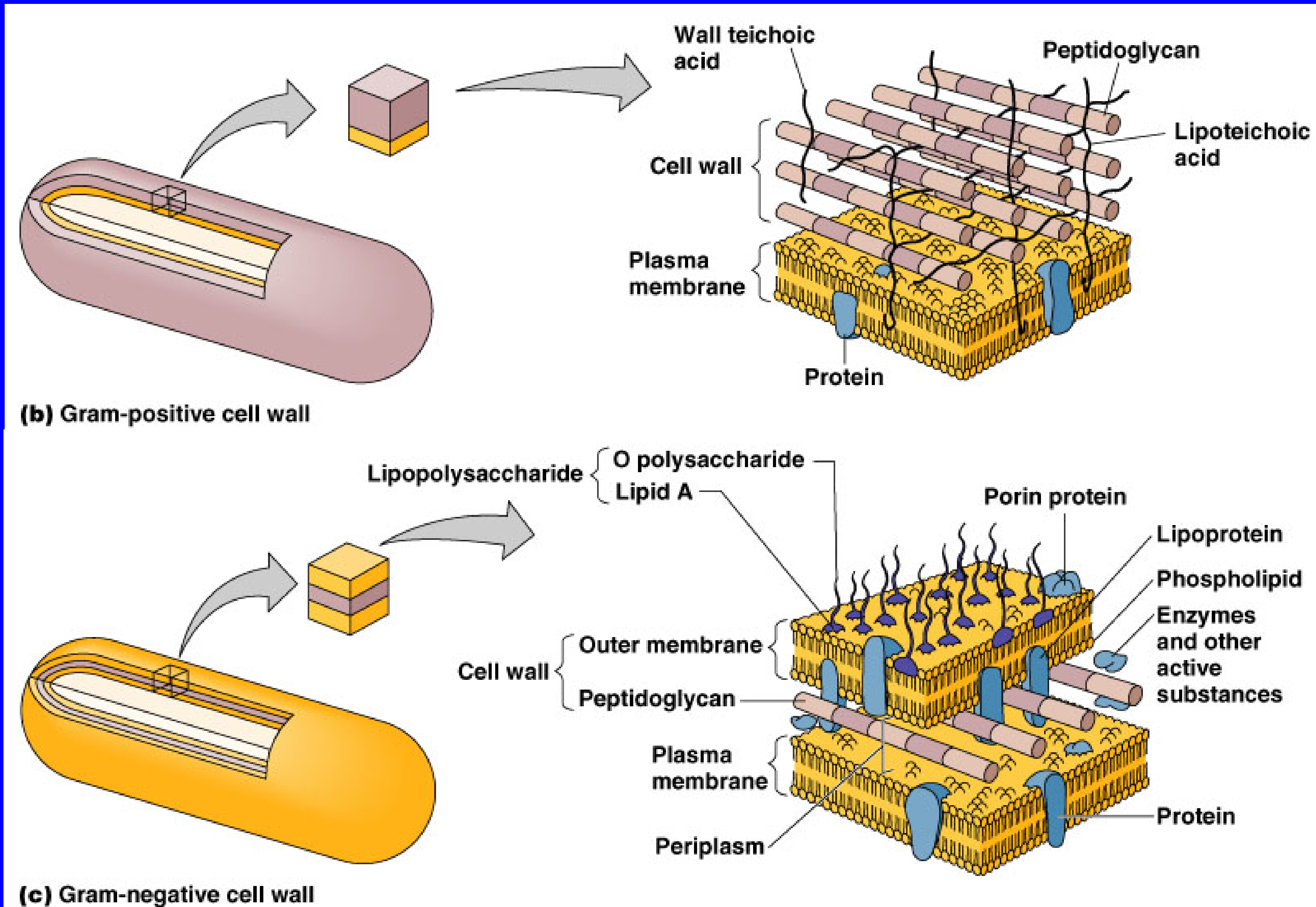


Figure 4.13b, c

Gram-Positive cell walls

- Teichoic acids:
  - Lipoteichoic acid links to plasma membrane
  - Wall teichoic acid links to peptidoglycan
- May regulate movement of cations
- Polysaccharides provide antigenic variation

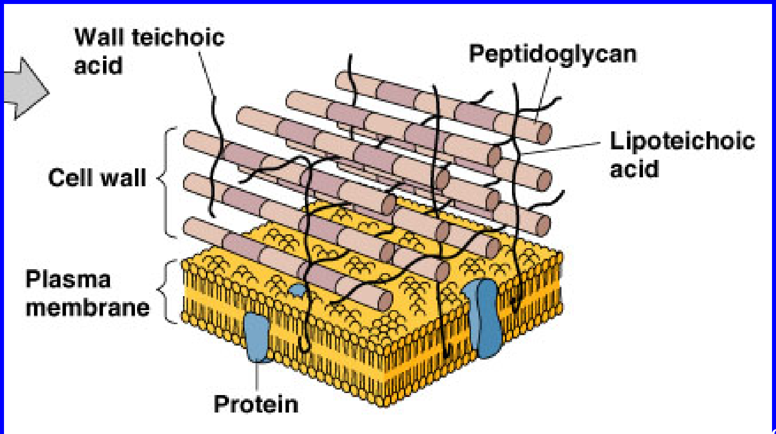


Figure 4.13b

teichoic acids

- polymers of glycerol or ribitol joined by phosphate groups

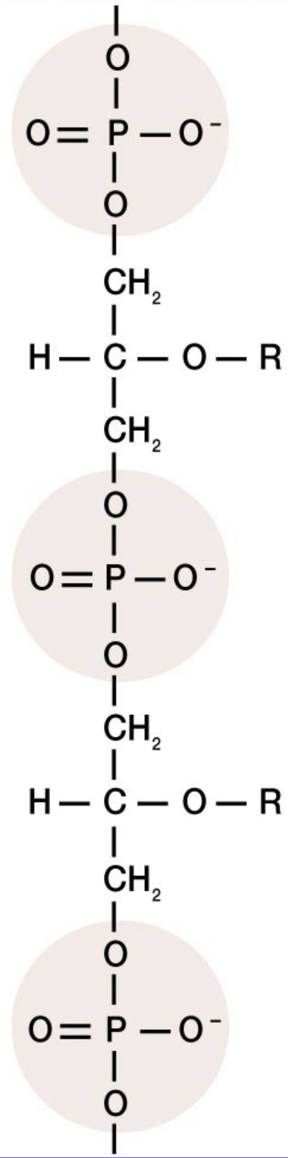
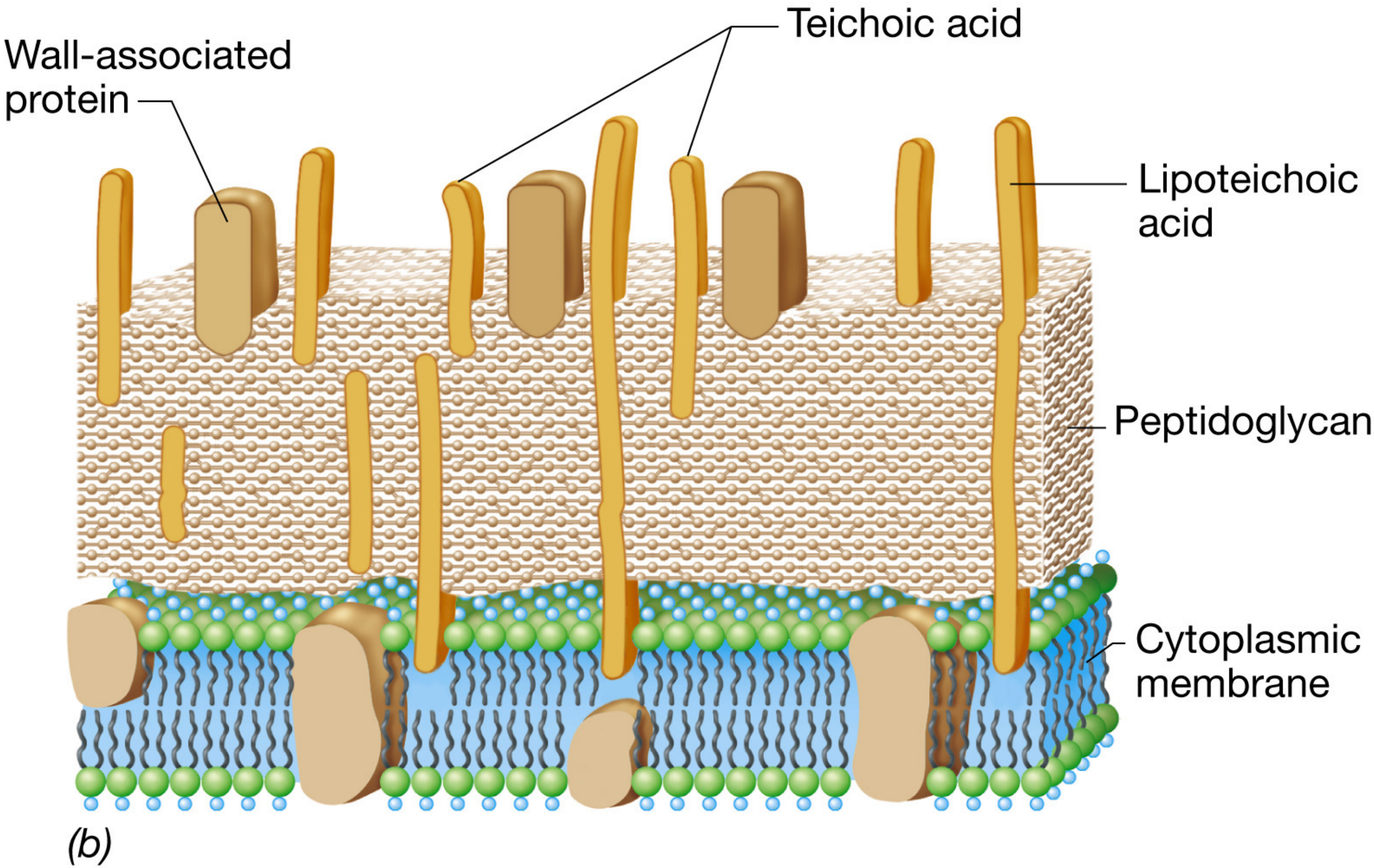


Figure 3.22


Teichoic acid
Wall-associated protein
Lipoteichoic acid
Peptidoglycan
Cytoplasmic membrane
(b)

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

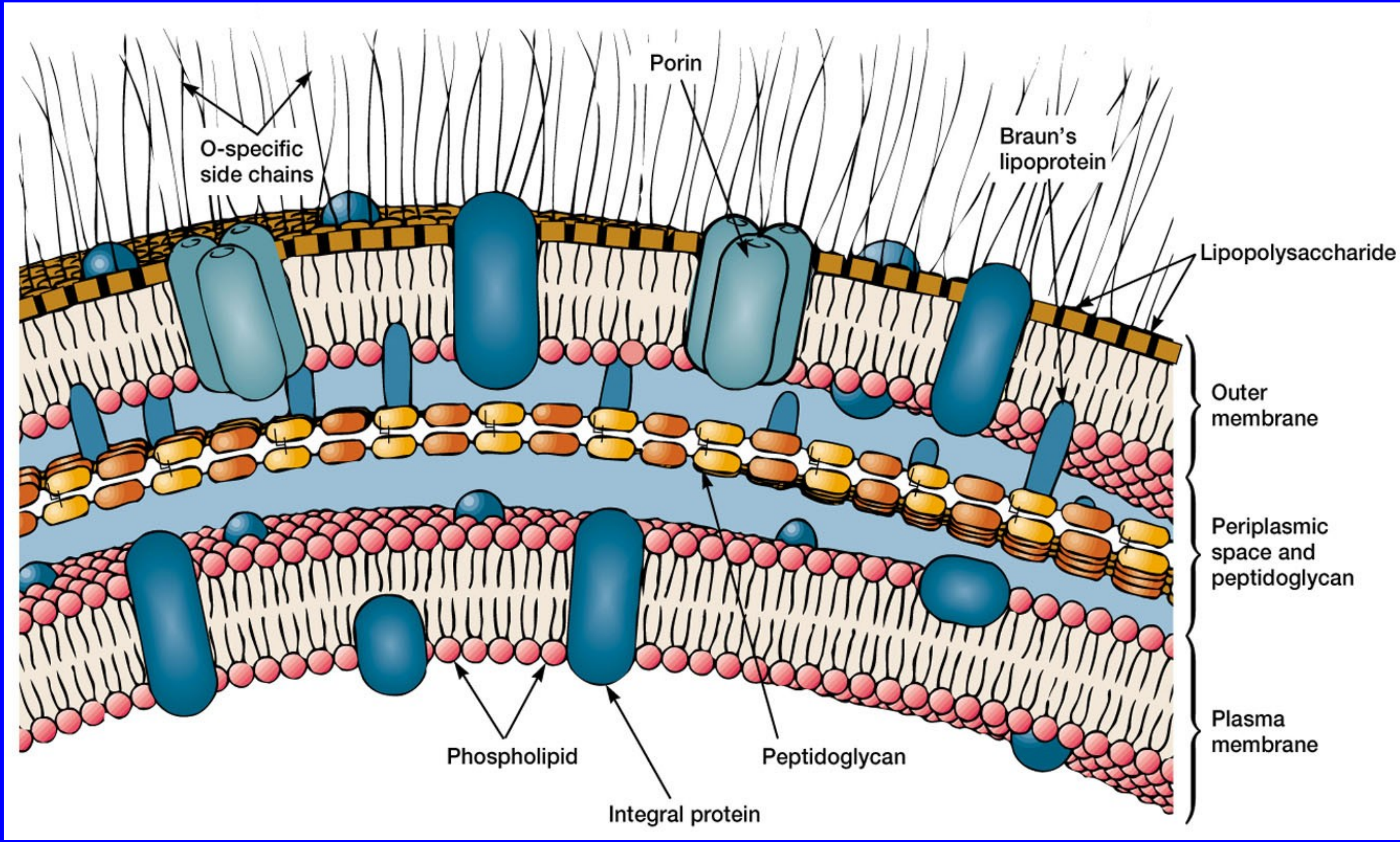
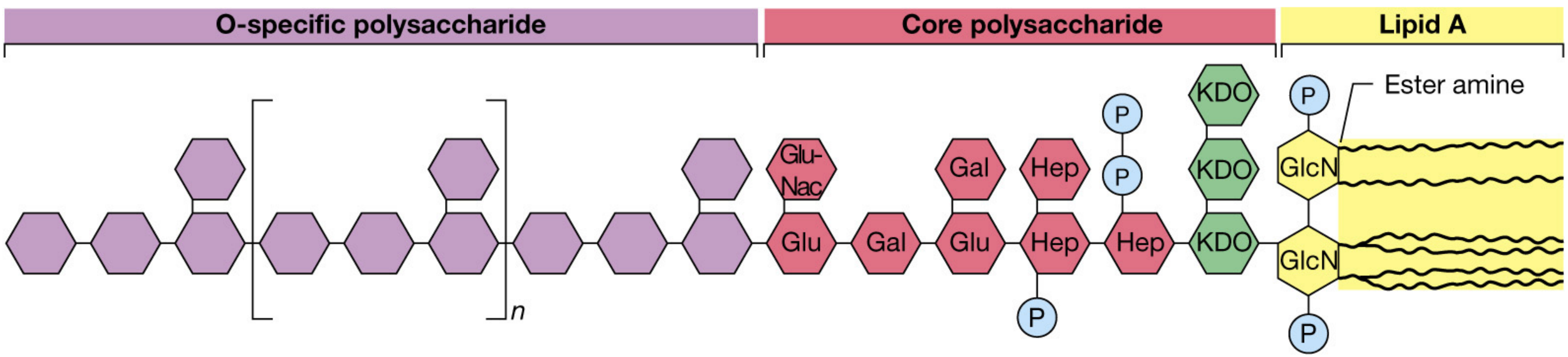

O-specific
side chains
Porin
Braun's
lipoprotein
Lipopolysaccharide
Outer
membrane
Periplasmic
space and
peptidoglycan
Plasma
membrane
Phospholipid
Peptidoglycan
Integral protein

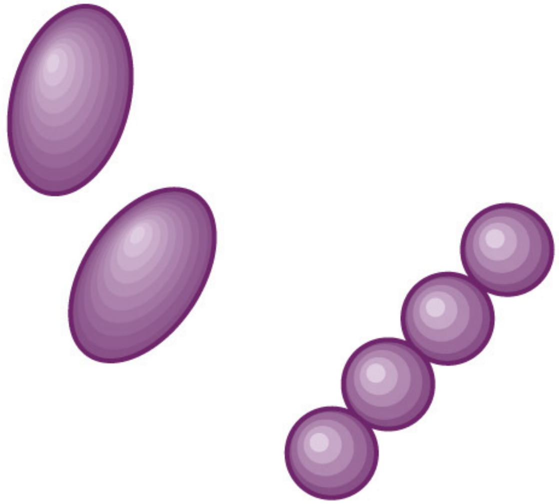
Figure 3.23


O-specific polysaccharide
Core polysaccharide
Lipid A
n
Glu-Nac
Glu
Gal
Gal
Glu
Hep
Hep
P
Hep
P
P
KDO
KDO
KDO
P
GlcN
GlcN
P
Ester amine

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

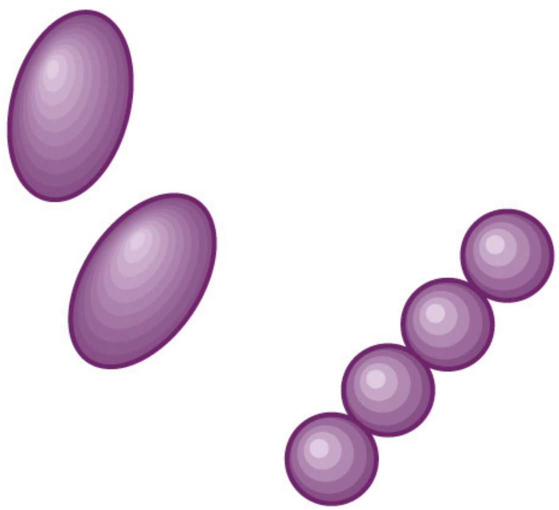
Step 1



Flood the heat-fixed smear with crystal violet for 1 min

All cells purple

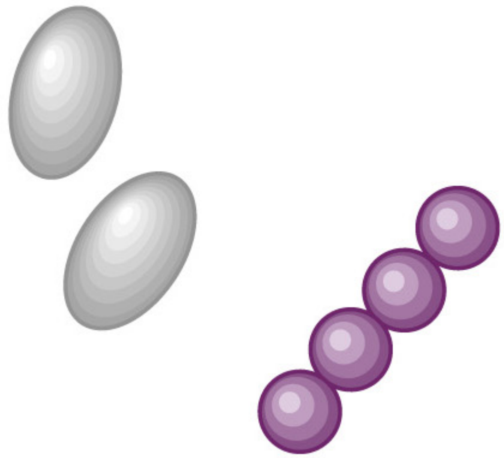
Step 2



Add iodine solution for 3 min

All cells remain purple

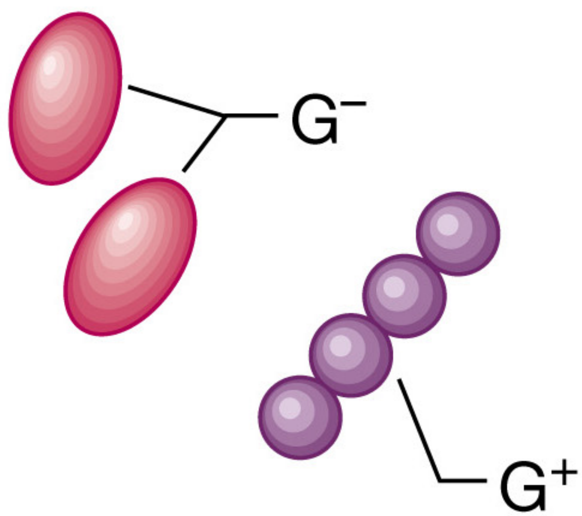
Step 3



Decolorize with alcohol briefly — about 20 sec

Gram-positive cells are purple; gram-negative cells are colorless

Step 4



Counterstain with safranin for 1–2 min

Gram-positive (G^+) cells are purple; gram-negative (G^-) cells are pink to red

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

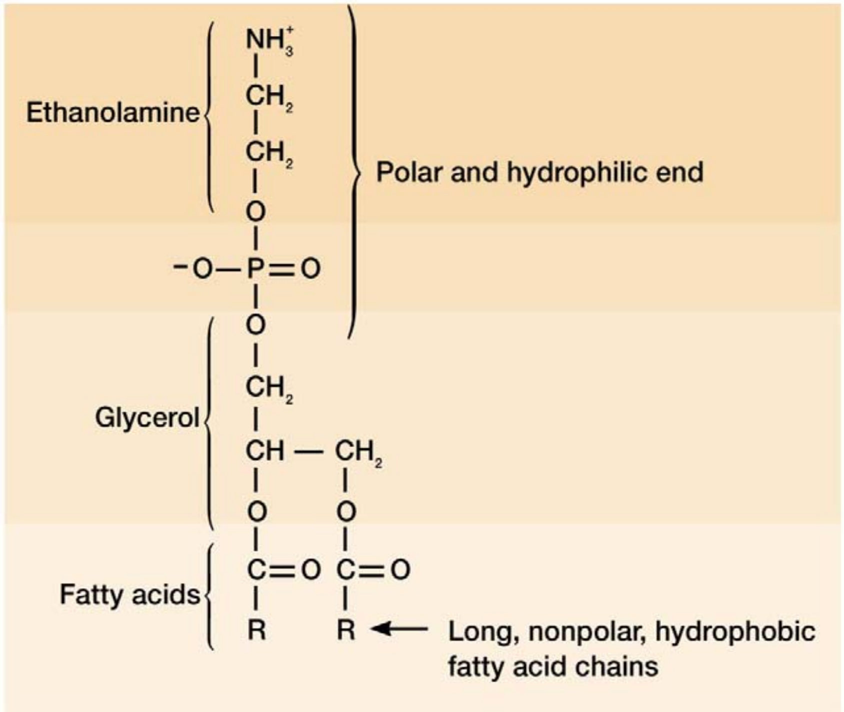
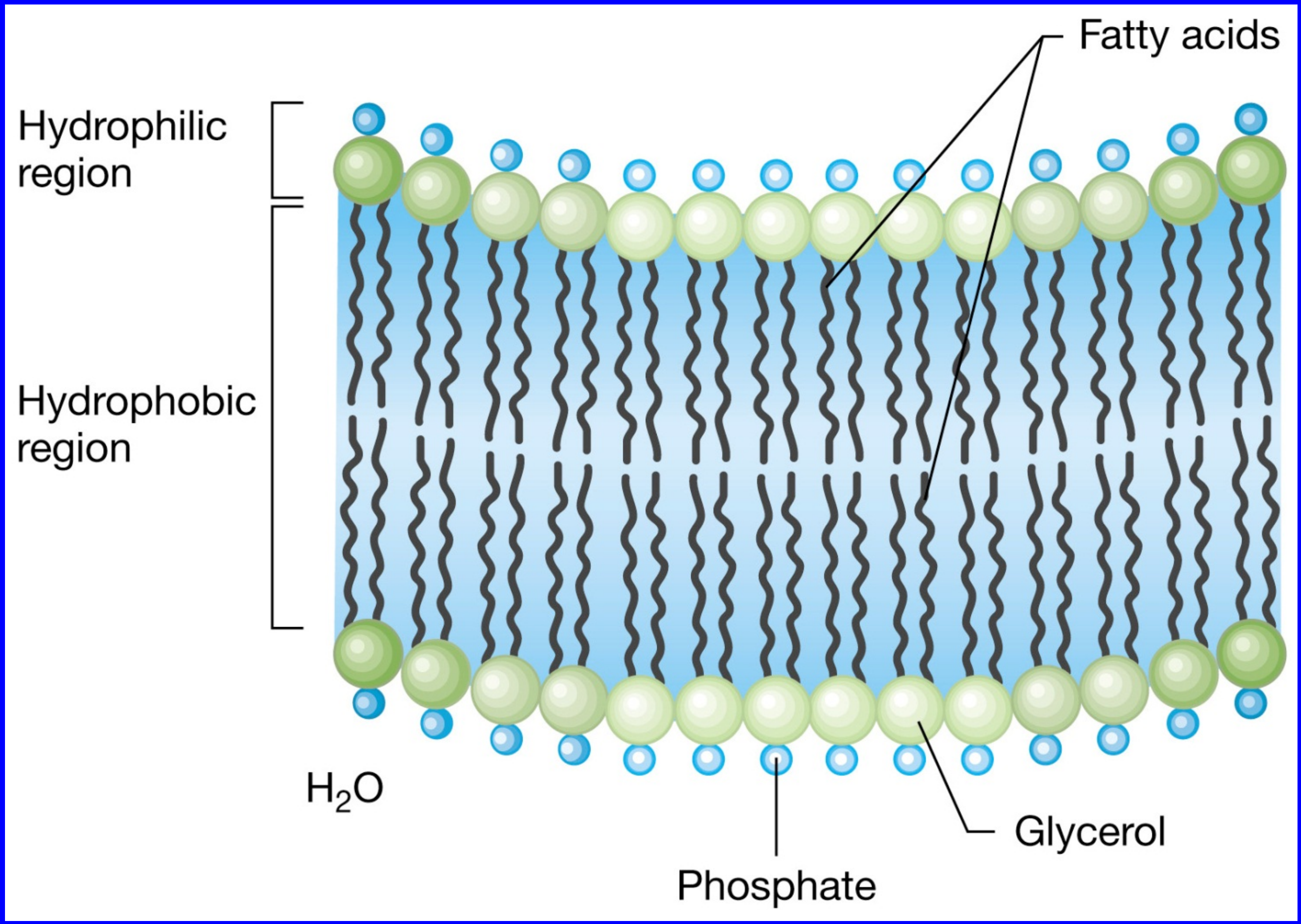


Figure 3.5

Lipid Bilayer



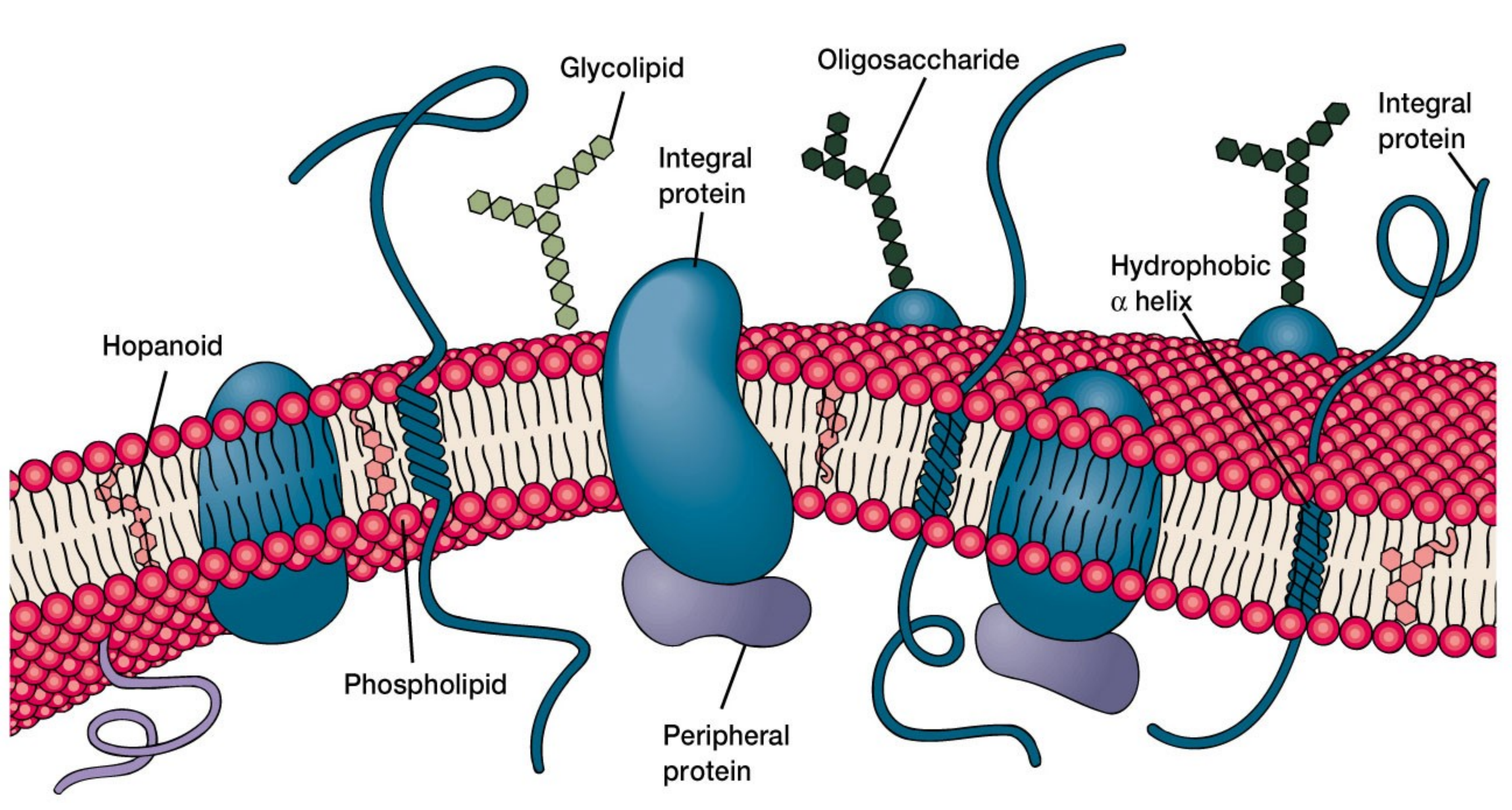


Figure 3.7 Fluid mosaic model of membrane structure

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**

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

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

The Cell Wall and Osmotic Protection

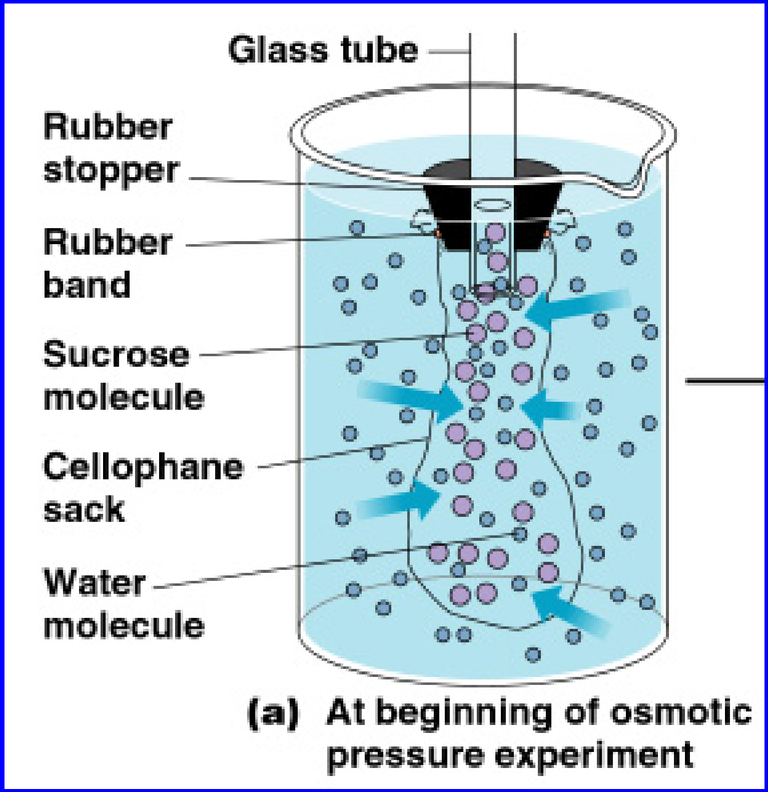
- **osmotic lysis**
  - can occur when cells are in hypotonic solutions
  - movement of water into cell causes swelling and lysis due to osmotic pressure
- cell wall protects against osmotic lysis

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**

- **Osmosis**
  - **Movement of water across a selectively permeable membrane from an area of high water concentration to an area of lower water.**
- **Osmotic pressure**
  - **The pressure needed to stop the movement of water across the membrane.**



(a) At beginning of osmotic pressure experiment

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**

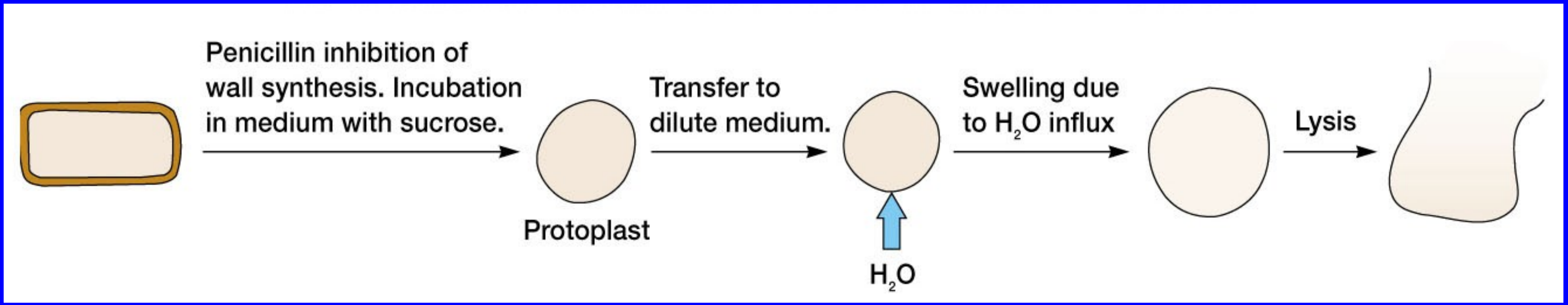


Figure 3.26

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

Membrane proteins

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

More functions…

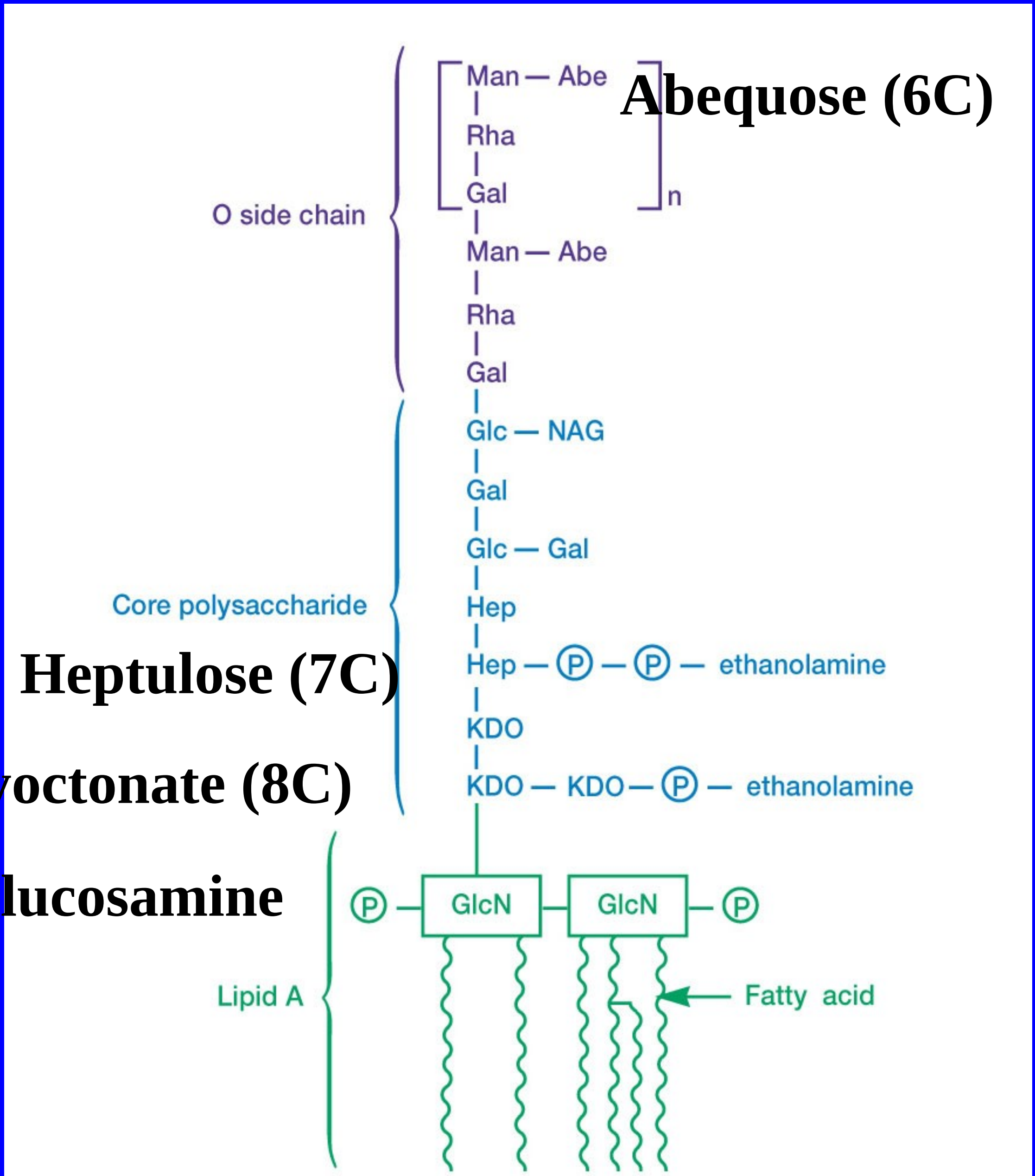
- **location of crucial metabolic processes**
- **detection of and response to chemicals in surroundings with the aid of special receptor molecules in the membrane**

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)



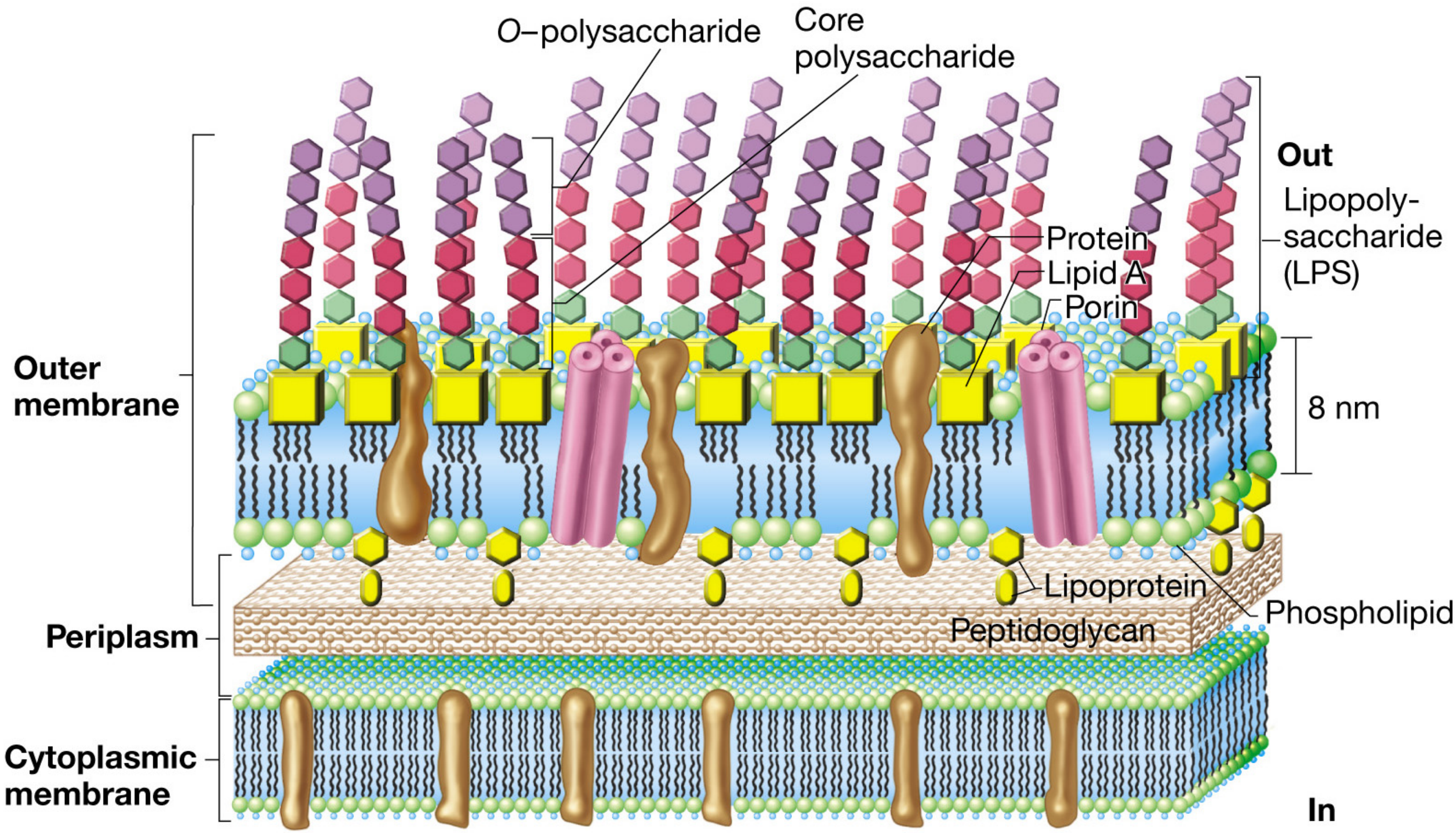
Abequose (6C)

Heptulose (7C)

2-keto-3-deoxyoctonate (8C)

glucosamine

Figure 3.25


O–polysaccharide
Core polysaccharide
Out
Lipopoly-saccharide (LPS)
Protein
Lipid A
Porin
8 nm
Outer membrane
Lipoprotein
Phospholipid
Peptidoglycan
Periplasm
Cytoplasmic membrane
In

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 endotoxin (lipid A)**

Endotoxin

- Lipid A released when cells lyse
- Causes systemic effects
  - Fever, Shock, Blood coagulation, Weakness, Diarrhea, Inflammation, Intestinal Hemorrhage, Fibrinolysis
- Effects are indirect, i.e., the LPS causes host systems to turn on including activating white cells, especially macophages and monocytes

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**

Examples of active transport

1. ATP- bindinq cassette transporter ABC transporter.

2. Svmport and antiport systems

3. Active transport by means of Group translocation or Phosphotransferase system.

4. Transport of iron

Movement Across Membranes

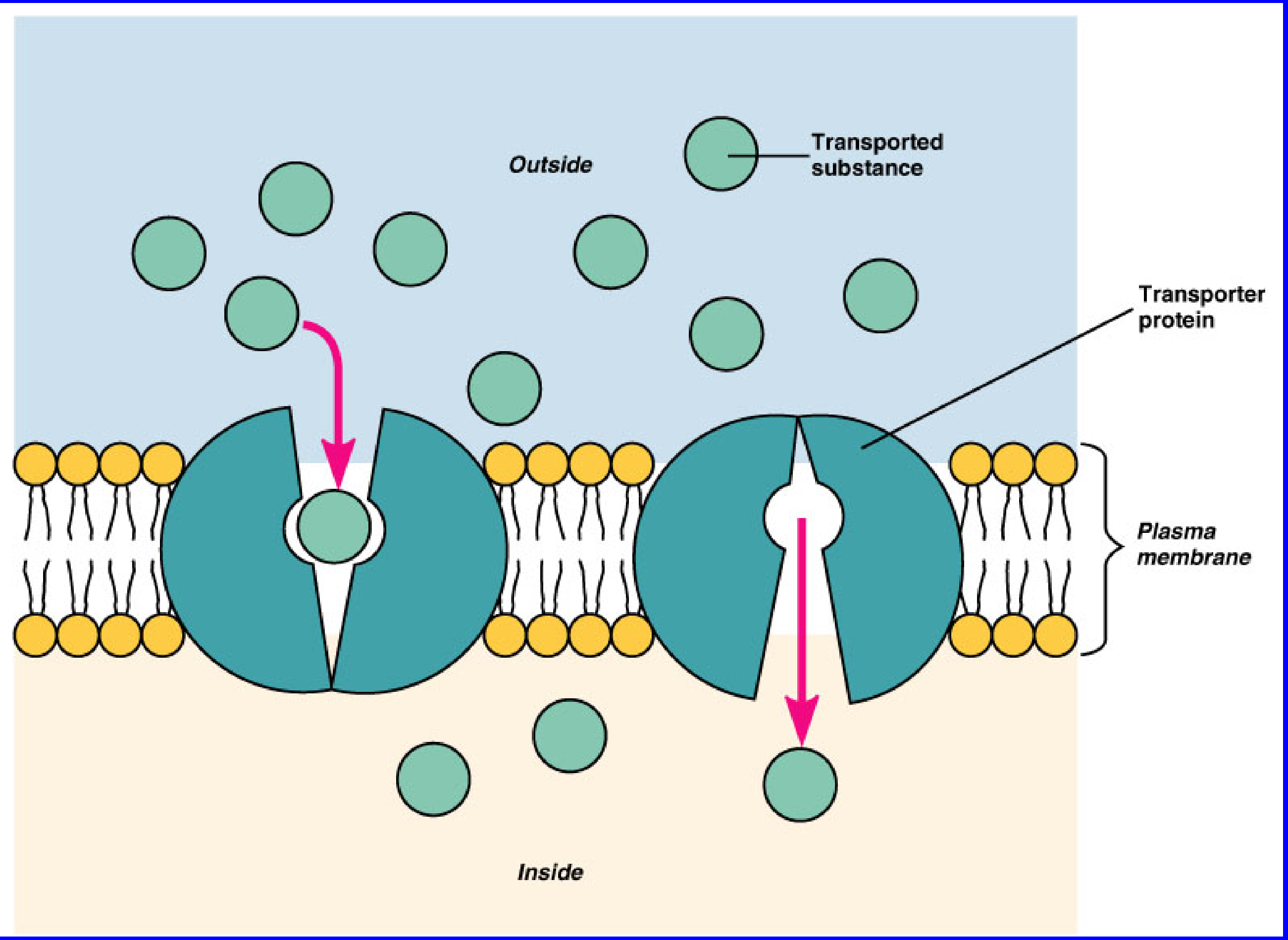


Figure 4.17

Transporter Proteins

Transport of nutrients and waste by bacteria (Usually small molecules: ions, amino-acids, sugars, purines and pyrimidines, vitamins, organic acids and alcohols, etc.

1. Passive diffusion

2. Facilitated diffusion

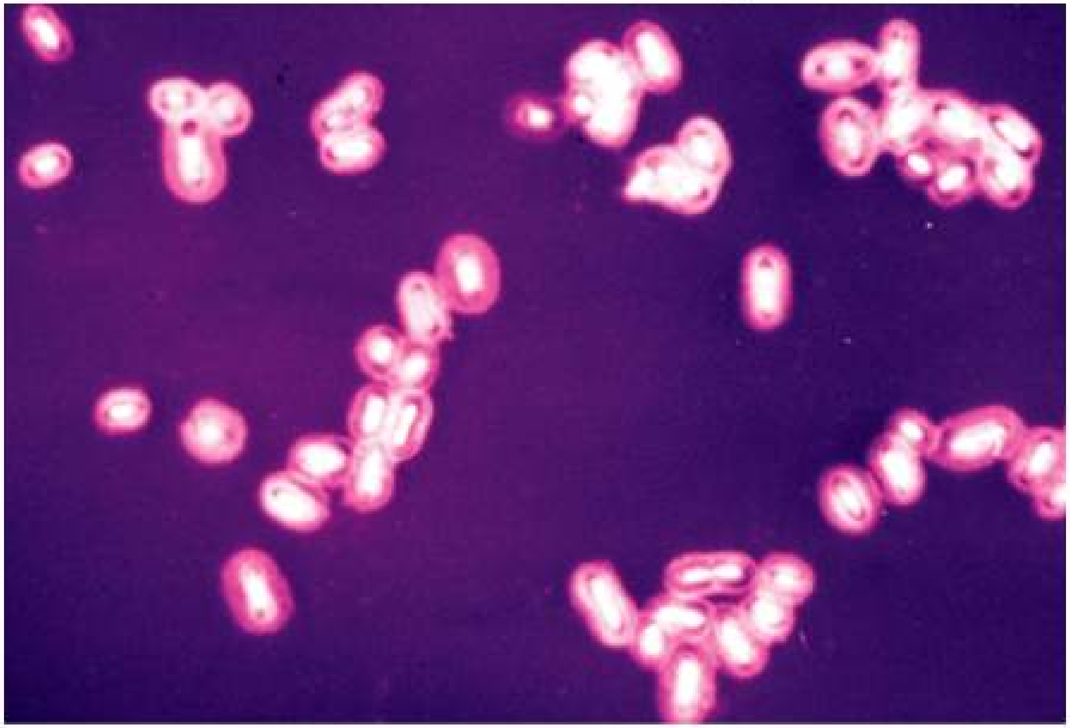
3. Active transport

Capsules, Slime Layers, and S-Layers

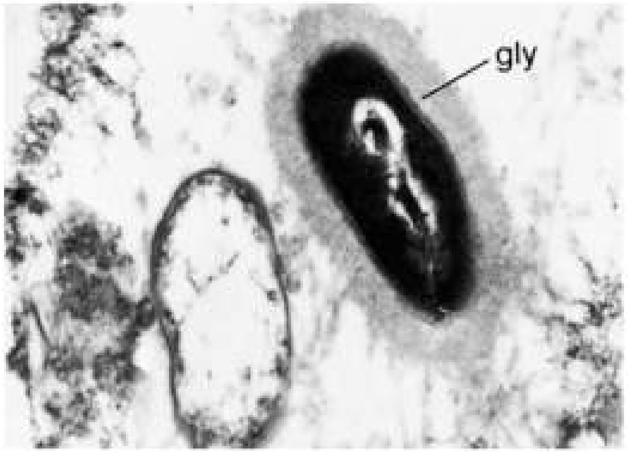
- layers of material lying outside the cell wall
  - capsules
    - usually composed of polysaccharides
    - well organized and not easily removed from cell
  - slime layers
    - similar to capsules except diffuse, unorganized and easily removed

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**



(a) *K. pneumoniae*



(b) *Bacteroides*

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**

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

Sporogenesis

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

The Bacterial Endospore

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

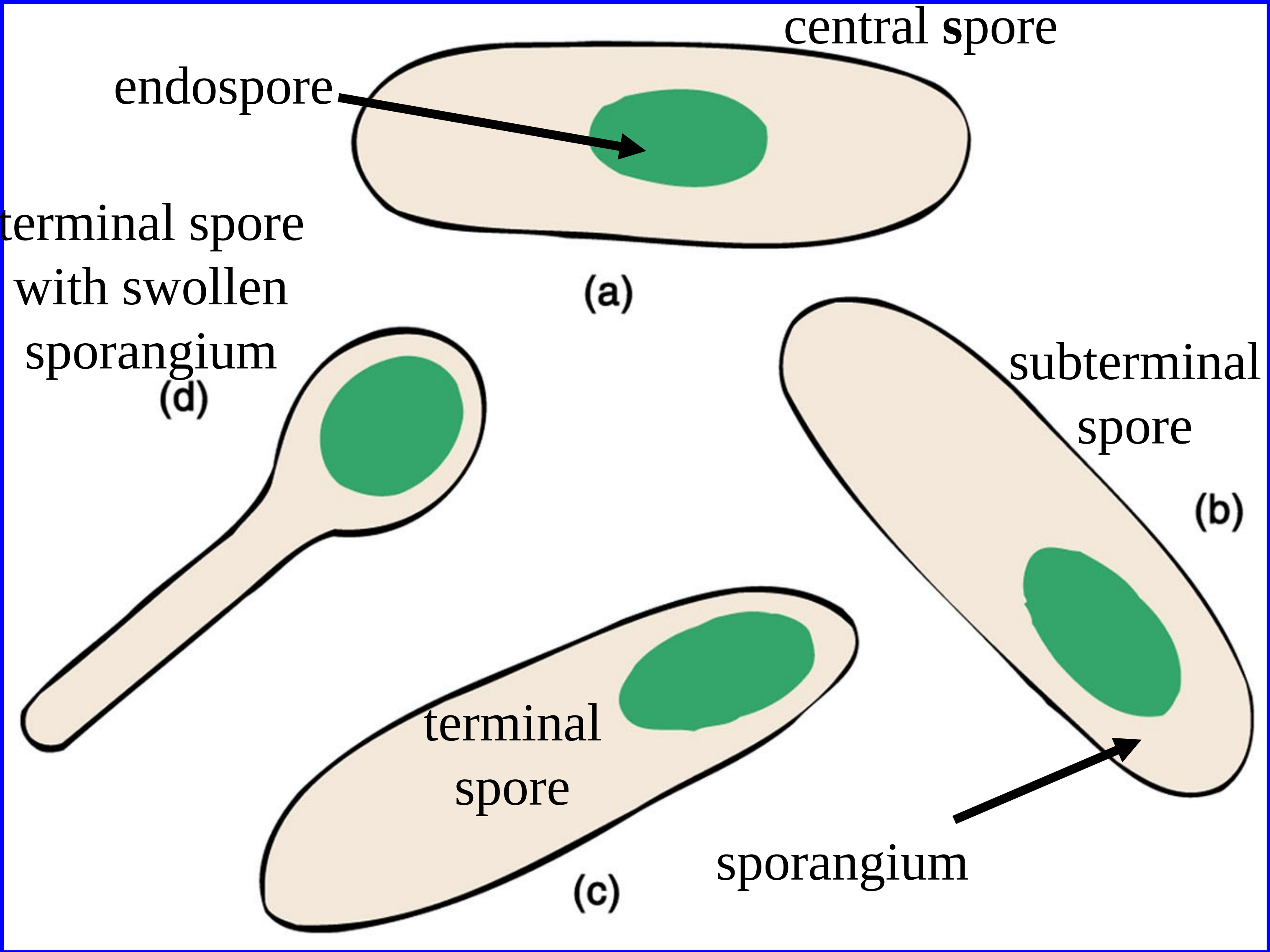

central spore
endospore
(a)
terminal spore
with swollen
sporangium
(d)
subterminal
spore
(b)
terminal
spore
(c)
sporangium

Figure 3.40

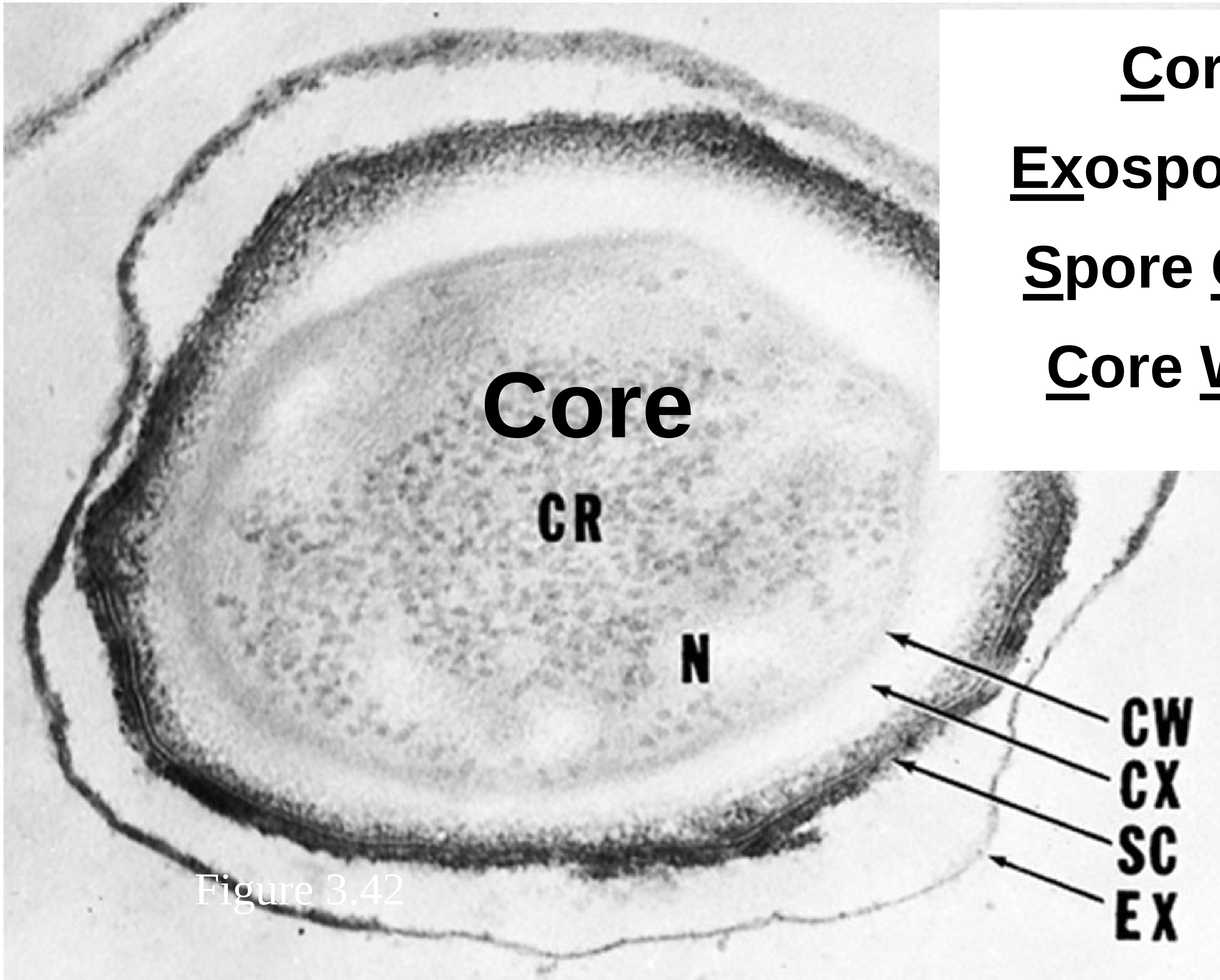


Figure 3.42

Cortex

Exosporium

Spore Coat

Core Wall

What makes an endospore so resistant?

- calcium (complexed with dipicolinic acid) in the core
- acid-soluble, DNA-binding proteins
- dehydrated core
- spore coat (protein layers)
- DNA repair enzymes (during germination)

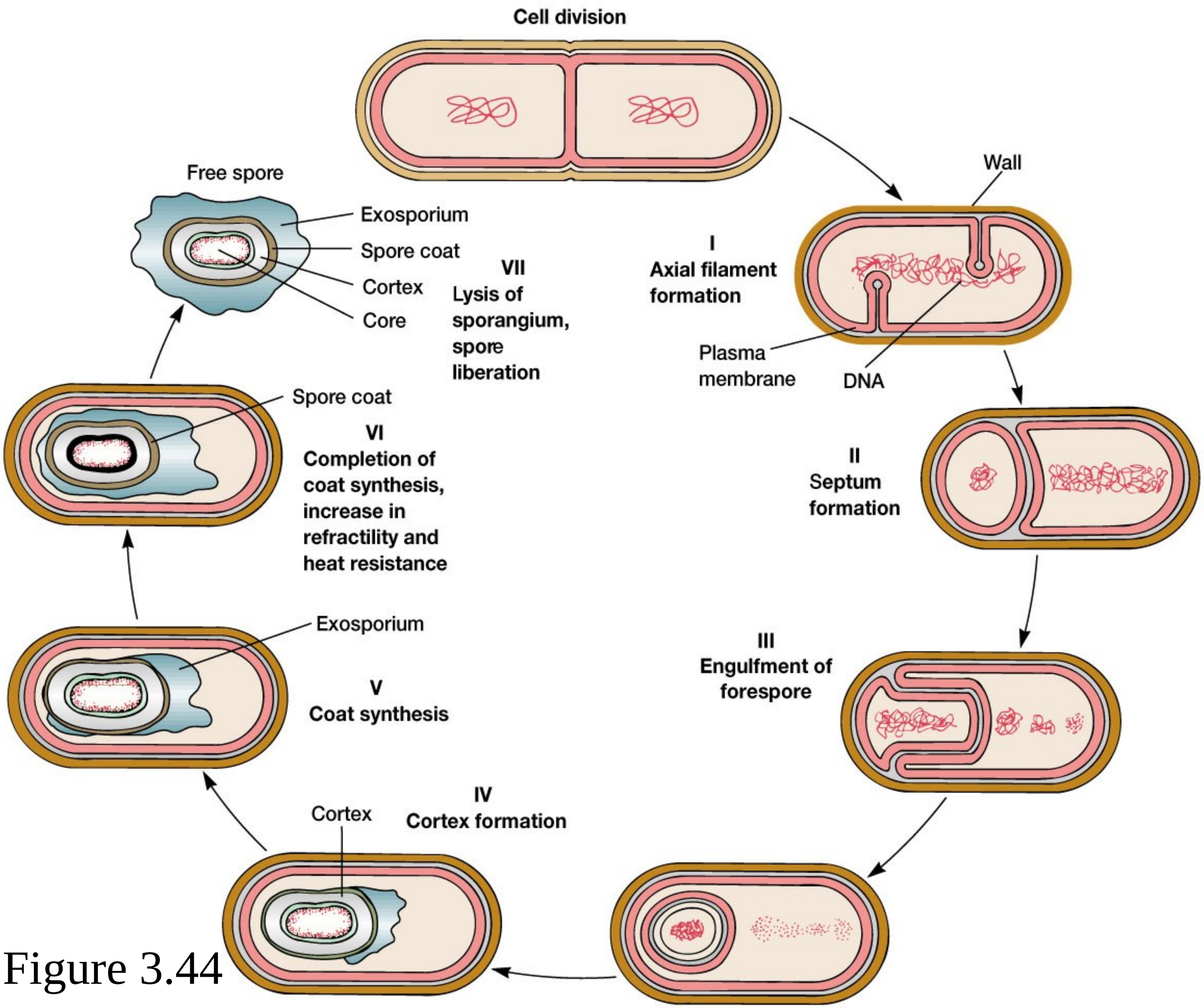

Cell division
Wall
I
Axial filament formation
Plasma membrane
DNA
II
Septum formation
III
Engulfment of forespore
IV
Cortex formation
Cortex
V
Coat synthesis
Exosporium
VI
Completion of coat synthesis, increase in refractility and heat resistance
Spore coat
VII
Lysis of sporangium, spore liberation
Free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

Figure 3.44

Transformation of endospore into vegetative cell

- **complex, multistage process**

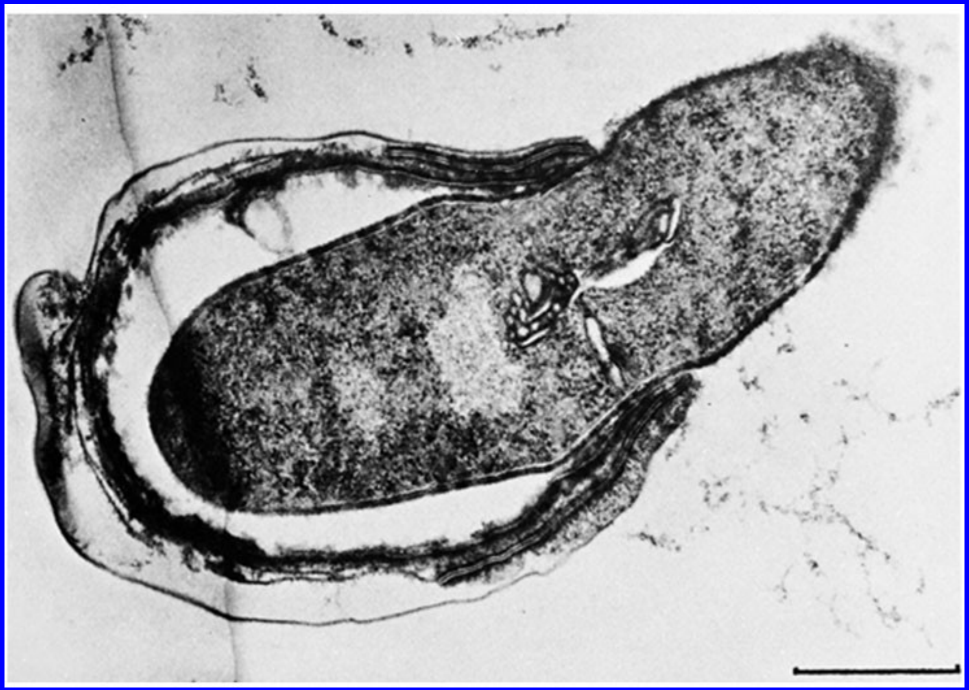


Figure 3.45

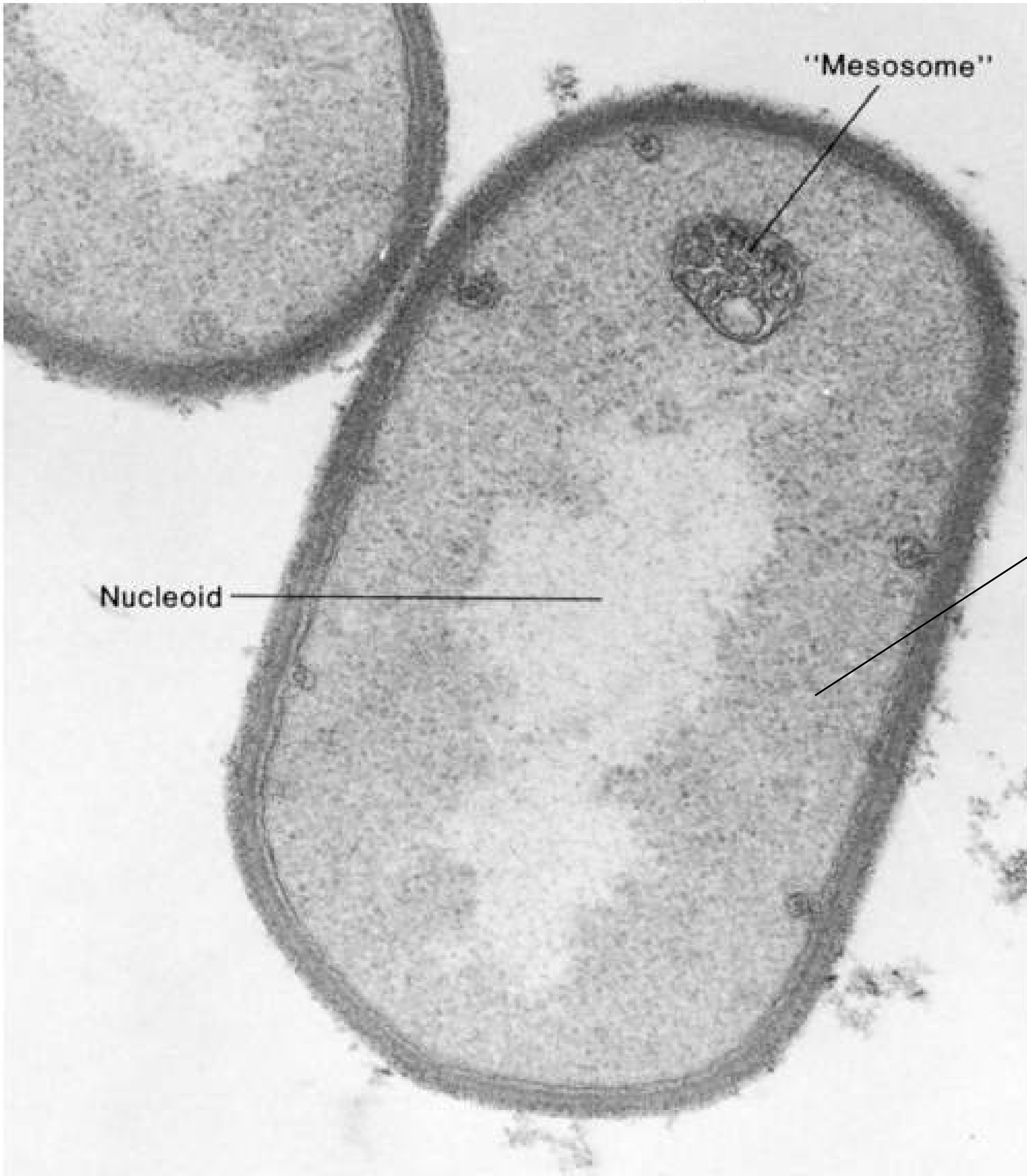
Stages in transformation

- 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

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

Inclusion Bodies

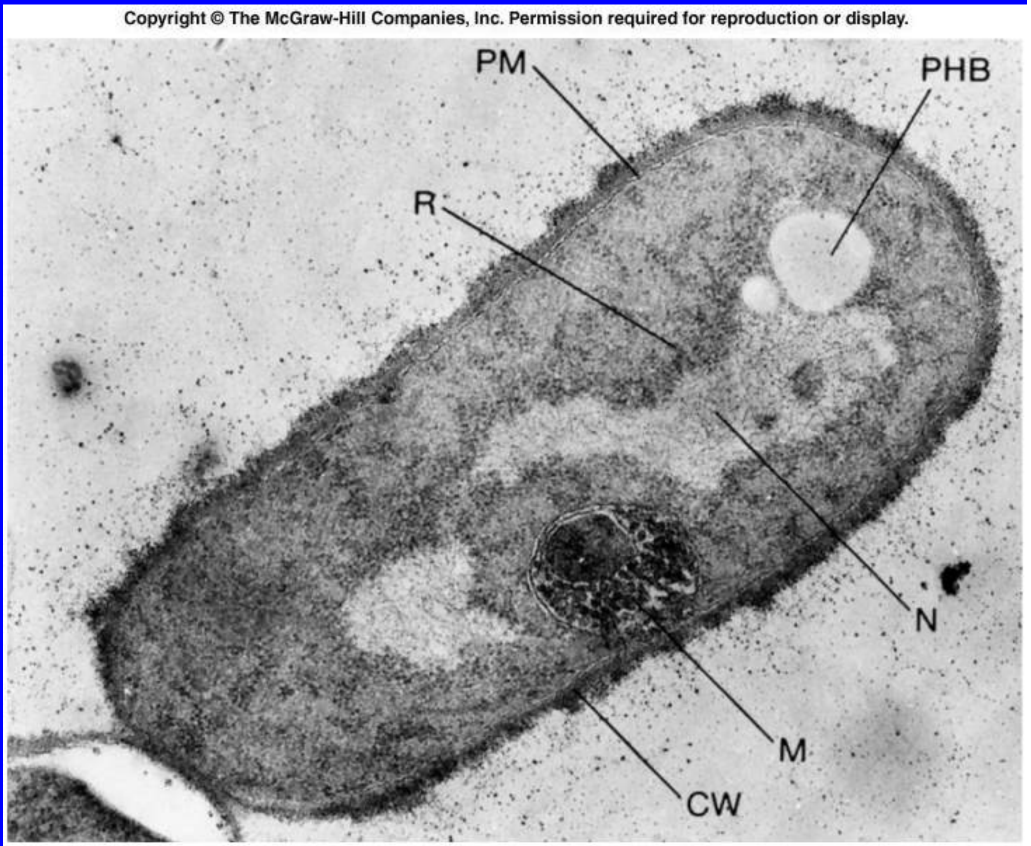
- granules of organic or inorganic material that are stockpiled by the cell for future use
- some are enclosed by a single-layered membrane
  - membranes vary in composition
  - some made of proteins; others contain lipids



Cytoplasmic Matrix

Organic inclusion bodies

- glycogen
  - polymer of glucose units (like starch)
- poly-ß-hydroxybutyrate (PHB)
- Both are for storing C for energy and biosynthesis



Organic inclusion bodies

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

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

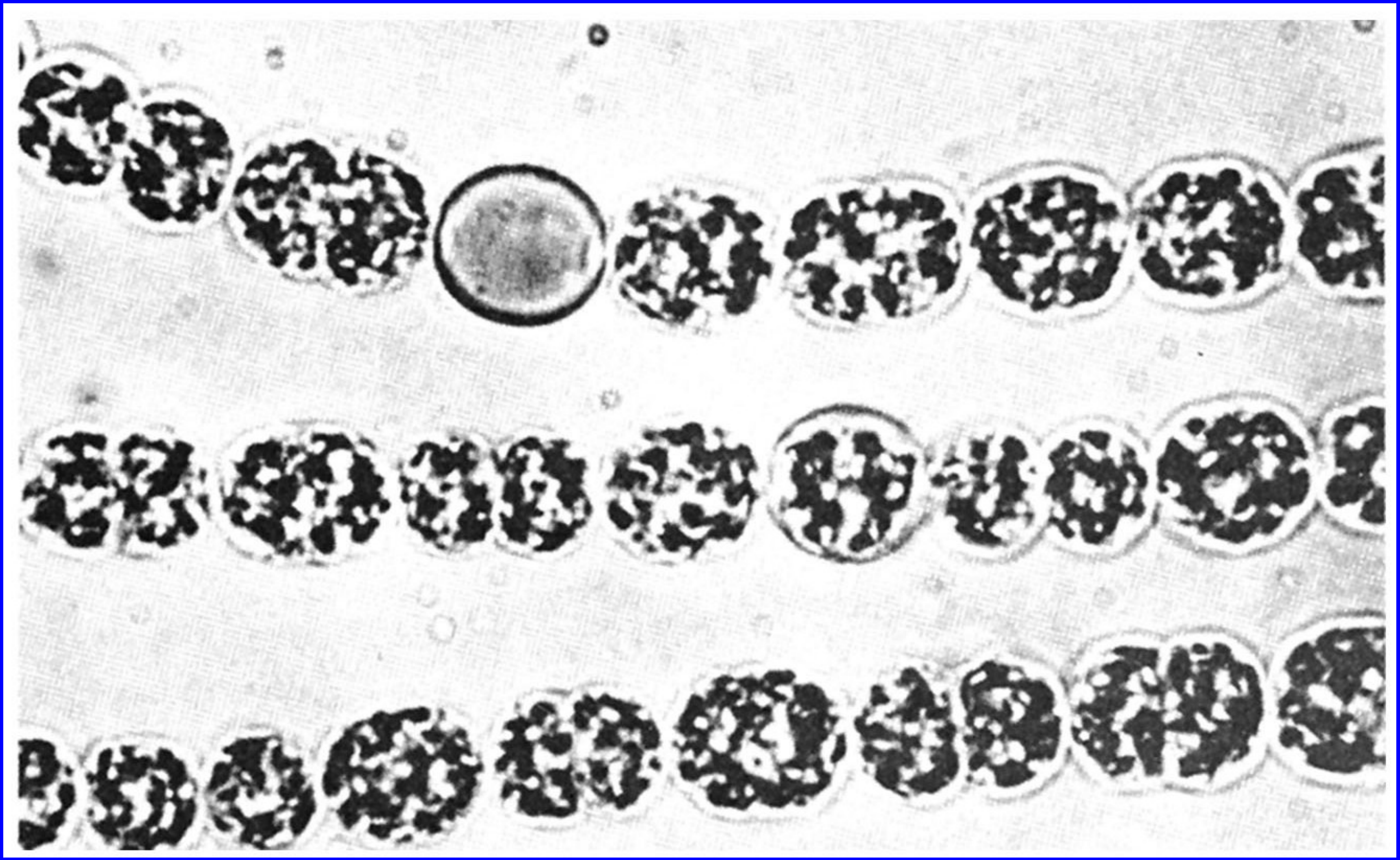
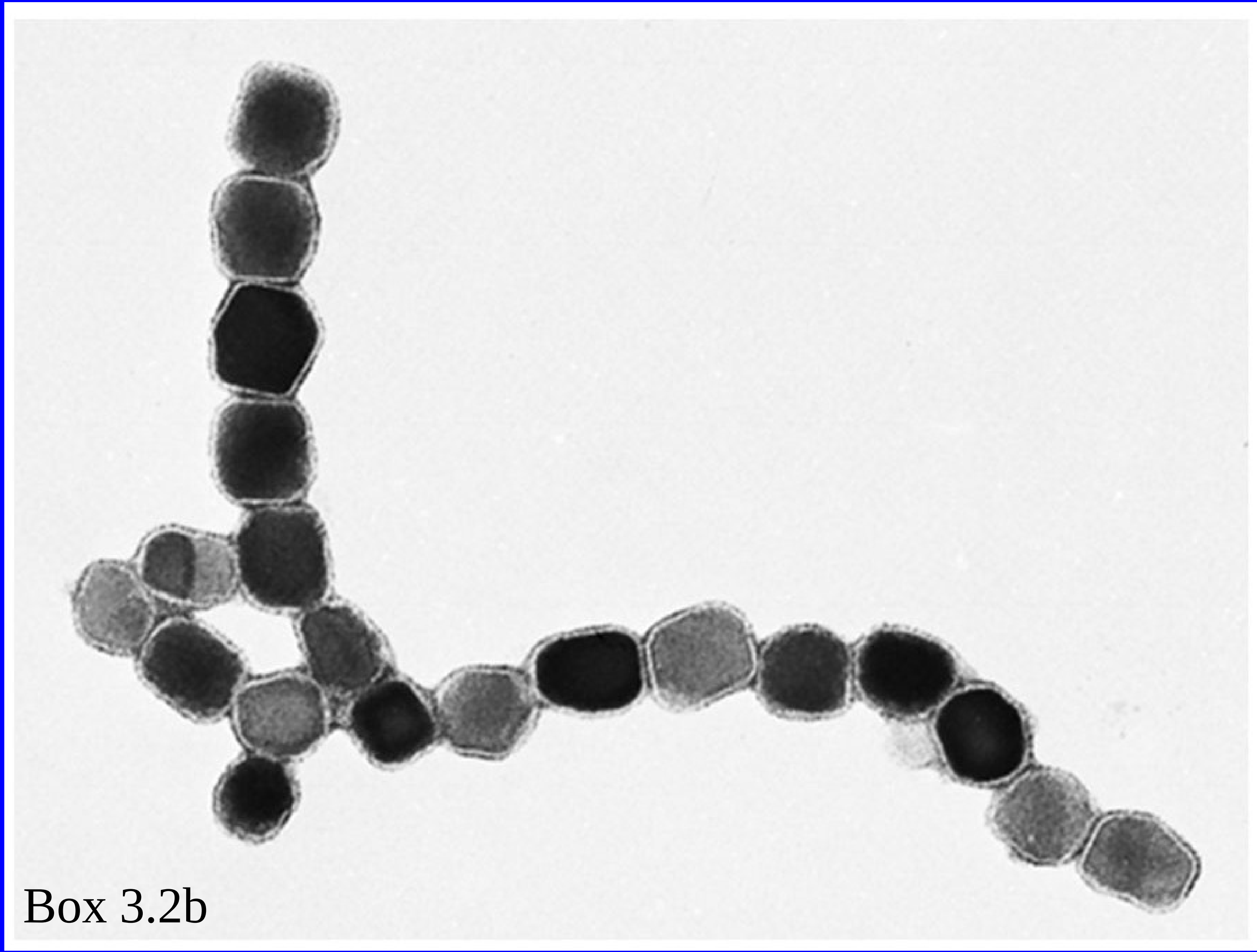


Figure 3.12a



Box 3.2b