Bacterial Cell Structure
Bacterial and Archaea Structure and Function

- Prokaryotes differ from eukaryotes in size and simplicity
  - most lack internal membrane systems
  - term prokaryotes is becoming blurred
  - this text will use *Bacteria* and *Archaea*
  - this chapter will cover *Bacteria* and their structures
Size, Shape, and Arrangement

• Shape
  – cocci and rods most common
  – various others

• Arrangement
  – determined by plane of division
  – determined by separation or not

• Size - varies
Shape and Arrangement-1

- 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
Shape and Arrangement-2

- bacilli (s., bacillus) – rods
  - coccobacilli – very short rods
- vibrios – resemble rods, comma shaped
- spirilla (s., spirillum) – rigid helices
- spirochetes – flexible helices
Shape and Arrangement-3

- mycelium – network of long, multinucleate filaments
- pleomorphic – organisms that are variable in shape
### Size

- **smallest** – 0.3 μm (*Mycoplasma*)
- **average rod** – 1.1 - 1.5 x 2 – 6 μm (*E. coli*)
- **very large** – 600 x 80 μm *Epulopiscium fishelsoni*

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Approximate diameter or width x length in nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oscillatoria Red blood cell</td>
<td>7,000</td>
</tr>
<tr>
<td><em>E. coli</em></td>
<td>1,300 x 4,000</td>
</tr>
<tr>
<td>Streptococcus</td>
<td>800–1,000</td>
</tr>
<tr>
<td>Poxvirus</td>
<td>230 x 320</td>
</tr>
<tr>
<td>Influenza virus</td>
<td>85</td>
</tr>
<tr>
<td>T2 <em>E.coli</em> bacteriophage</td>
<td>65 x 95</td>
</tr>
<tr>
<td>Tobacco mosaic virus</td>
<td>15 x 300</td>
</tr>
<tr>
<td>Poliomyelitis virus</td>
<td>27</td>
</tr>
</tbody>
</table>
Size – Shape Relationship

- important for nutrient uptake
- surface to volume ratio (S/V)
- small size may be protective mechanism from predation

\[
\begin{align*}
\text{r} &= 1 \text{ mm} \\
\text{Surface area} &= 12.6 \text{ mm}^2 \\
\text{Volume} &= 4.2 \text{ mm}^3 \\
\frac{\text{Surface}}{\text{Volume}} &= 3
\end{align*}
\]

\[
\begin{align*}
\text{r} &= 2 \text{ mm} \\
\text{Surface area} &= 50.3 \text{ mm}^2 \\
\text{Volume} &= 33.5 \text{ mm}^3 \\
\frac{\text{Surface}}{\text{Volume}} &= 1.5
\end{align*}
\]
Bacterial Cell Organization

Common Features

- **Cell envelope** – 3 layers
  - Plasma membrane
  - Cell wall
  - Layers outside the cell – glycocalyx (capsule, S layer, slime layer)

- **Cytoplasm**
  - Nucleoid and plasmids
  - Ribosomes
  - Inclusion bodies
  - Cytoskeleton
  - Intracytoplasmic membranes

- **External structures**
  - Flagella
  - Fimbriae
  - Pili
<table>
<thead>
<tr>
<th>Structure</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma membrane</td>
<td>Selectively permeable barrier, mechanical boundary of cell, nutrient and waste transport, location of many metabolic processes (respiration, photosynthesis), detection of environmental cues for chemotaxis</td>
</tr>
<tr>
<td>Gas vacuole</td>
<td>An inclusion that provides buoyancy for floating in aquatic environments</td>
</tr>
<tr>
<td>Ribosomes</td>
<td>Protein synthesis</td>
</tr>
<tr>
<td>Inclusions</td>
<td>Storage of carbon, phosphate, and other substances</td>
</tr>
<tr>
<td>Nucleoid</td>
<td>Localization of genetic material (DNA)</td>
</tr>
<tr>
<td>Periplasmic space</td>
<td>In typical Gram-negative bacteria, contains hydrolytic enzymes and binding proteins for nutrient processing and uptake; in typical Gram-positive bacteria, may be smaller or absent</td>
</tr>
<tr>
<td>Cell wall</td>
<td>Protection from osmotic stress, helps maintain cell shape</td>
</tr>
<tr>
<td>Capsules and slime layers</td>
<td>Resistance to phagocytosis, adherence to surfaces</td>
</tr>
<tr>
<td>Fimbriae and pili</td>
<td>Attachment to surfaces, bacterial conjugation and transformation, twitching and gliding motility</td>
</tr>
<tr>
<td>Flagella</td>
<td>Swimming and swarming motility</td>
</tr>
<tr>
<td>Endospore</td>
<td>Survival under harsh environmental conditions</td>
</tr>
</tbody>
</table>
Bacterial Cell Envelope

• Plasma membrane
• Cell wall
• Layers outside the cell wall
Plasma Membrane Functions

- Absolute requirement for all living organisms
- Some bacteria also have internal membranes
  Encompasses the cytoplasm
- Selectively permeable barrier
- Interacts with external environment
  - receptors for detection of and response to chemicals in surroundings
  - transport systems
  - metabolic processes
Fluid Mosaic Model of Membrane

Lipid bilayers with floating proteins

- amphipathic lipids
  - polar ends (hydrophilic – interact with water)
  - non-polar tails (hydrophobic – insoluble in water)
- membrane proteins
  - Peripheral
    - loosely connected to membrane and easily removed
  - Integral
    - amphipathic – embedded within membrane
    - carry out important functions
Bacterial Lipids

• Saturation levels of membrane lipids reflect environmental conditions such as temperature

• Bacterial membranes lack sterols but do contain sterol-like molecules, **hopanoids**
  – stabilize membrane
  – found in petroleum

(a) Cholesterol (a steroid) is found in the membranes of eukaryotes.

(b) Bacteriohopanetetrol (a hopanoid) is found in many bacterial membranes.
Uptake of Nutrients – Getting Through the Barrier

• Macroelements (macronutrients)
  – C, O, H, N, S, P
    • found in organic molecules such as proteins, lipids, carbohydrates, and nucleic acids
  – K, Ca, Mg, and Fe
    • cations and serve in variety of roles including enzymes, biosynthesis
  – required in relatively large amounts
Uptake of Nutrients – Getting Through the Barrier

• Micronutrients (trace elements)
  – Mn, Zn, Co, Mo, Ni, and Cu
  – required in trace amounts
  – often supplied in water or in media components
  – ubiquitous in nature
  – serve as enzymes and cofactors

• Some unique substances may be required
Uptake of Nutrients – Getting Through the Barrier

• Growth factors
  – organic compounds
  – essential cell components (or their precursors) that the cell cannot synthesize
  – must be supplied by environment if cell is to survive and reproduce
Classes of Growth Factors

- amino acids
  - needed for protein synthesis
- purines and pyrimidines
  - needed for nucleic acid synthesis
- vitamins
  - function as enzyme cofactors
- heme
Uptake of Nutrients

- Microbes can only take in dissolved particles across a selectively permeable membrane.
- Some nutrients enter by passive diffusion.
- Microorganisms use transport mechanisms:
  - facilitated diffusion – all microorganisms
  - active transport – all microorganisms
  - group translocation – *Bacteria* and *Archaea*
  - endocytosis – *Eukarya* only
Bacterial Cell Wall

• Peptidoglycan (murein)
  – rigid structure that lies just outside the cell plasma membrane
  – two types based on structure which shows up with Gram stain
    • Gram-positive: stain purple; thick peptidoglycan
    • Gram-negative: stain pink or red; thin peptidoglycan and outer membrane
Cell Wall Functions

• Maintains shape of the bacterium
  – almost all bacteria have one
• Helps protect cell from osmotic lysis
• Helps protect from toxic materials
• May contribute to pathogenicity
Peptidoglycan Structure

- Meshlike polymer of identical subunits forming long strands
  - two alternating sugars
    - $N$-acetylglucosamine (NAG)
    - $N$-acetylmuramic acid
  - alternating D- and L-amino acids
Strands Are Crosslinked

- Peptidoglycan strands have a helical shape
- Peptidoglycan chains are crosslinked by peptides for strength
  - interbridges may form
  - peptidoglycan sacs – interconnected networks
  - various structures occur
Gram-Positive Cell Walls

- Composed primarily of peptidoglycan
- May also contain teichoic acids (negatively charged)
  - help maintain cell envelope
  - protect from environmental substances
  - may bind to host cells
- Some gram-positive bacteria have layer of proteins on surface of peptidoglycan
Periplasmic Space of Gram + Bacteria

- Lies between plasma membrane and cell wall and is smaller than that of Gram-negative bacteria
- Periplasm has relatively few proteins
- Enzymes secreted by Gram-positive bacteria are called exoenzymes
  - aid in degradation of large nutrients
Gram-Negative Cell Walls

- More complex than Gram-positive
- Consist of a thin layer of peptidoglycan surrounded by an outer membrane
- Outer membrane composed of lipids, lipoproteins, and lipopolysaccharide (LPS)
- No teichoic acids
Gram-Negative Cell Walls

• Peptidoglycan is ~5-10% of cell wall weight

• Periplasmic space differs from that in Gram-positive cells
  – may constitute 20–40% of cell volume
  – many enzymes present in periplasm
    • hydrolytic enzymes, transport proteins and other proteins
Gram-Negative Cell Walls

- outer membrane lies outside the thin peptidoglycan layer
- Braun’s lipoproteins connect outer membrane to peptidoglycan
- other adhesion sites reported
Lipopolysaccharide (LPS)

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

- Lipid A embedded in outer membrane
- Core polysaccharide, O side chain extend out from the cell
Characteristics of LPS

• contributes to negative charge on cell surface
• helps stabilize outer membrane structure
• may contribute to attachment to surfaces and biofilm formation
• creates a permeability barrier
  – More permeable than plasma membrane due to presence of porin proteins and transporter proteins
• protection from host defenses (O antigen)
• can act as an endotoxin (lipid A)
Mechanism of Gram Stain Reaction

- Gram stain reaction due to nature of cell wall
- shrinkage of the pores of peptidoglycan layer of Gram-positive cells
  - constriction prevents loss of crystal violet during decolorization step
- thinner peptidoglycan layer and larger pores of Gram-negative bacteria does not prevent loss of crystal violet
Cells that Lose a Cell Wall May Survive in Isotonic Environments

- Protoplasts
- Spheroplasts
- *Mycoplasma*
  - does not produce a cell wall
  - plasma membrane more resistant to osmotic pressure
Components Outside of the Cell Wall

- Outermost layer in the cell envelope
- Glycocalyx
  - capsules and slime layers
  - S layers
- Aid in attachment to each other and to other surfaces
  - e.g., biofilms in plants and animals
- Protection for the cell
Capsules

- Usually composed of polysaccharides
- Well organized and not easily removed from cell
- Visible in light microscope
- Protective advantages
  - resistant to phagocytosis
  - protect from desiccation
  - exclude viruses and detergents
- Associated with specific bacteria
Slime Layers

• similar to capsules except diffuse, unorganized and easily removed
• slime may aid in motility
• associated with most bacteria
S Layers

- Regularly structured layers of protein or glycoprotein that self-assemble
  - in Gram-negative bacteria the S layer adheres to outer membrane
  - in Gram-positive bacteria it is associated with the peptidoglycan surface
S Layer Functions

- Protect from ion and pH fluctuations, osmotic stress, enzymes, and predation
- Maintains shape and rigidity
- Promotes adhesion to surfaces
- Protects from host defenses
- Potential use in nanotechnology
  - S layer spontaneously associates
Bacterial Cytoplasmic Structures

• Cytoskeleton
• Intracytoplasmic membranes
• Inclusions
• Ribosomes
• Nucleoid and plasmids
Protoplast and Cytoplasm

- Protoplast is plasma membrane and everything within
- Cytoplasm - material bounded by the plasmid membrane
The Cytoskeleton

- Homologs of all 3 eukaryotic cytoskeletal elements have been identified in bacteria
- Functions are similar as in eukaryotes

<table>
<thead>
<tr>
<th>Table 3.2 Bacterial Cytoskeletal Proteins</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
</tr>
<tr>
<td><strong>Tubulin Homologues</strong></td>
</tr>
<tr>
<td>FtsZ</td>
</tr>
<tr>
<td>BtubA/BtubB</td>
</tr>
<tr>
<td>TubZ</td>
</tr>
<tr>
<td><strong>Actin Homologues</strong></td>
</tr>
<tr>
<td>MamK</td>
</tr>
<tr>
<td>MreB/Mbl</td>
</tr>
<tr>
<td>ParM</td>
</tr>
<tr>
<td><strong>Intermediate Filament Homologues</strong></td>
</tr>
<tr>
<td>CreS (crescentin)</td>
</tr>
<tr>
<td><strong>Unique Bacterial Cytoskeletal Proteins</strong></td>
</tr>
<tr>
<td>MinD</td>
</tr>
<tr>
<td>ParA</td>
</tr>
</tbody>
</table>
Intracytoplasmic Membranes

- Plasma membrane infoldings
  - observed in many photosynthetic bacteria
  - observed in many bacteria with high respiratory activity
Inclusions

• 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
  – may be referred to as microcompartments
Storage Inclusions

• Storage of nutrients, metabolic end products, energy, building blocks
• Glycogen storage
• Carbon storage
  – poly-β-hydroxybutyrate (PHB)
• Phosphate - Polyphosphate (Volutin)
• Amino acids - cyanophycin granules
Storage Inclusions

(a) [Image of a cell with labeled parts: PM, PHB, R, CW, N]

(b) [Image of a cluster of bacteria with labeled PHB]

Reprinted from The Shorter Bergey’s Manual of Determinative Bacteriology, 6e, John G. Holt, Editor, 1977 © Bergey’s Manual Trust. Published by Williams & Wilkins Baltimore, MD
Microcompartments

- Not bound by membranes but compartmentalized for a specific function
- Carboxysomes - CO$_2$ fixing bacteria
- Gas vacuoles
  - found in aquatic, photosynthetic bacteria and archaea
  - provide buoyancy in gas vesicles
Other Inclusions

- **Magnetosomes**
  - found in aquatic bacteria
  - magnetite particles for orientation in Earth’s magnetic field
  - cytoskeletal protein
    - helps form magnetosome chain
Ribosomes

- Complex protein/RNA structures
  - sites of protein synthesis
  - bacterial and archaea ribosome = 70S
  - eukaryotic (80S) S = Svedburg unit
- Bacterial ribosomal RNA
  - 16S small subunit
  - 23S and 5S in large subunit
The Nucleoid

- Usually not membrane bound (few exceptions)
- Location of chromosome and associated proteins
- Usually 1 closed circular, double-stranded DNA molecule
- Supercoiling and nucleoid proteins aid in folding
Plasmids

- Extrachromosomal DNA
  - found in bacteria, archaea, some fungi
  - usually small, closed circular DNA molecules

- Exist and replicate independently of chromosome
  - **Episomes**: when integrated into chromosome
  - inherited during cell division

- Contain few genes that are **non-essential**
  - confer selective advantage to host (e.g., drug resistance, enzyme production)

- Classification based on mode of existence, spread, and function
<table>
<thead>
<tr>
<th>Type</th>
<th>Function</th>
<th>Example</th>
<th>Size (kbp)</th>
<th>Hosts</th>
<th>Phenotypic Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conjugative Plasmids</td>
<td>Transfer of DNA from one cell to another</td>
<td>F factor</td>
<td>95–100</td>
<td><em>E. coli</em>, <em>Salmonella</em>, <em>Citrobacter</em></td>
<td>Sex pilus, conjugation</td>
</tr>
<tr>
<td>R Plasmids</td>
<td>Carry antibiotic-resistance genes</td>
<td>RP4</td>
<td>54</td>
<td><em>Pseudomonas</em> and many other Gram-negative bacteria</td>
<td>Sex pilus, conjugation, resistance to Amp, Km, Nm, Tet</td>
</tr>
<tr>
<td>Col Plasmids</td>
<td>Produce bacteriocins, substances that destroy closely related species</td>
<td>ColE1</td>
<td>9</td>
<td><em>E. coli</em></td>
<td>Colicin E1 production</td>
</tr>
<tr>
<td>Virulence Plasmids</td>
<td>Carry virulence genes</td>
<td>Ti</td>
<td>200</td>
<td><em>Agrobacterium tumefaciens</em></td>
<td>Tumor induction in plants</td>
</tr>
<tr>
<td>Metabolic Plasmids</td>
<td>Carry genes for enzymes</td>
<td>CAM</td>
<td>230</td>
<td><em>Pseudomonas</em></td>
<td>Camphor degradation</td>
</tr>
</tbody>
</table>

1 Abbreviations used for resistance to antibiotics: Amp, ampicillin; Gm, gentamycin; Km, kanamycin; Nm, neomycin; Tet, tetracycline.
2 Many R plasmids, metabolic plasmids, and others are also conjugative.
External Structures

• Extend beyond the cell envelope in bacteria
• Function in protection, attachment to surfaces, horizontal gene transfer, cell movement
  – pili and fimbriae
  – flagella
Pili and Fimbriae

- Fimbriae (s., fimbria); pili (s., pilus)
  - short, thin, hairlike, proteinaceous appendages (up to 1,000/cell)
  - can mediate attachment to surfaces, motility, DNA uptake

- Sex pili (s., pilus)
  - longer, thicker, and less numerous (1-10/cell)
  - genes for formation found on plasmids
  - required for conjugation
Flagella

• Threadlike, locomotor appendages extending outward from plasma membrane and cell wall

• Functions
  – motility and swarming behavior
  – attachment to surfaces
  – may be virulence factors
Bacterial Flagella

• Thin, rigid protein structures that cannot be observed with bright-field microscope unless specially stained
• Ultrastructure composed of three parts
• Pattern of flagellation varies
Patterns of Flagella Distribution

- **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
Three Parts of Flagella

• Filament
  – extends from cell surface to the tip
  – hollow, rigid cylinder of flagellin protein

• Hook
  – links filament to basal body

• Basal body
  – series of rings that drive flagellar motor
Motility

• Flagellar movement
• Spirochete motility
• Twitching motility
• Gliding motility
Motility

- *Bacteria* and *Archaea* have directed movement
- Chemotaxis
  - move toward chemical attractants such as nutrients, away from harmful substances
- Move in response to temperature, light, oxygen, osmotic pressure, and gravity
Bacterial Flagellar Movement

- Flagellum rotates like a propeller
  - very rapid rotation up to 1100 revolutions/sec
  - in general, counterclockwise (CCW) rotation causes forward motion (run)
  - in general, clockwise rotation (CW) disrupts run causing cell to stop and tumble
Spirochete Motility

- Multiple flagella form axial fibril which winds around the cell
- Flagella remain in periplasmic space inside outer sheath
- Corkscrew shape exhibits flexing and spinning movements
Twitching and Gliding Motility

- May involve pili and slime
- Twitching
  - pili at ends of cell
  - short, intermittent, jerky motions
  - cells are in contact with each other and surface
- Gliding
  - smooth movements
The Bacterial Endospore

- Complex, dormant structure formed by some bacteria
- Various locations within the cell
- Resistant to numerous environmental conditions
  - heat
  - radiation
  - chemicals
  - desiccation
Endospore Structure

- Spore surrounded by thin covering called exosporium
- Thick layers of protein form the spore coat
- Cortex, beneath the coat, thick peptidoglycan
- Core has nucleoid and ribosomes
What Makes an Endospore so Resistant?

• Calcium (complexed with dipicolinic acid)
• Small, acid-soluble, DNA-binding proteins (SASPs)
• Dehydrated core
• Spore coat and exosporium protect
Sporulation

- Process of endospore formation
- Occurs in hours (up to 10 hours)
- Normally commences when growth ceases because of lack of nutrients
- Complex multistage process
Formation of Vegetative Cell

• Activation
  – prepares spores for germination
  – often results from treatments like heating

• Germination
  – environmental nutrients are detected
  – spore swelling and rupture of absorption of spore coat
  – increased metabolic activity

• Outgrowth - emergence of vegetative cell