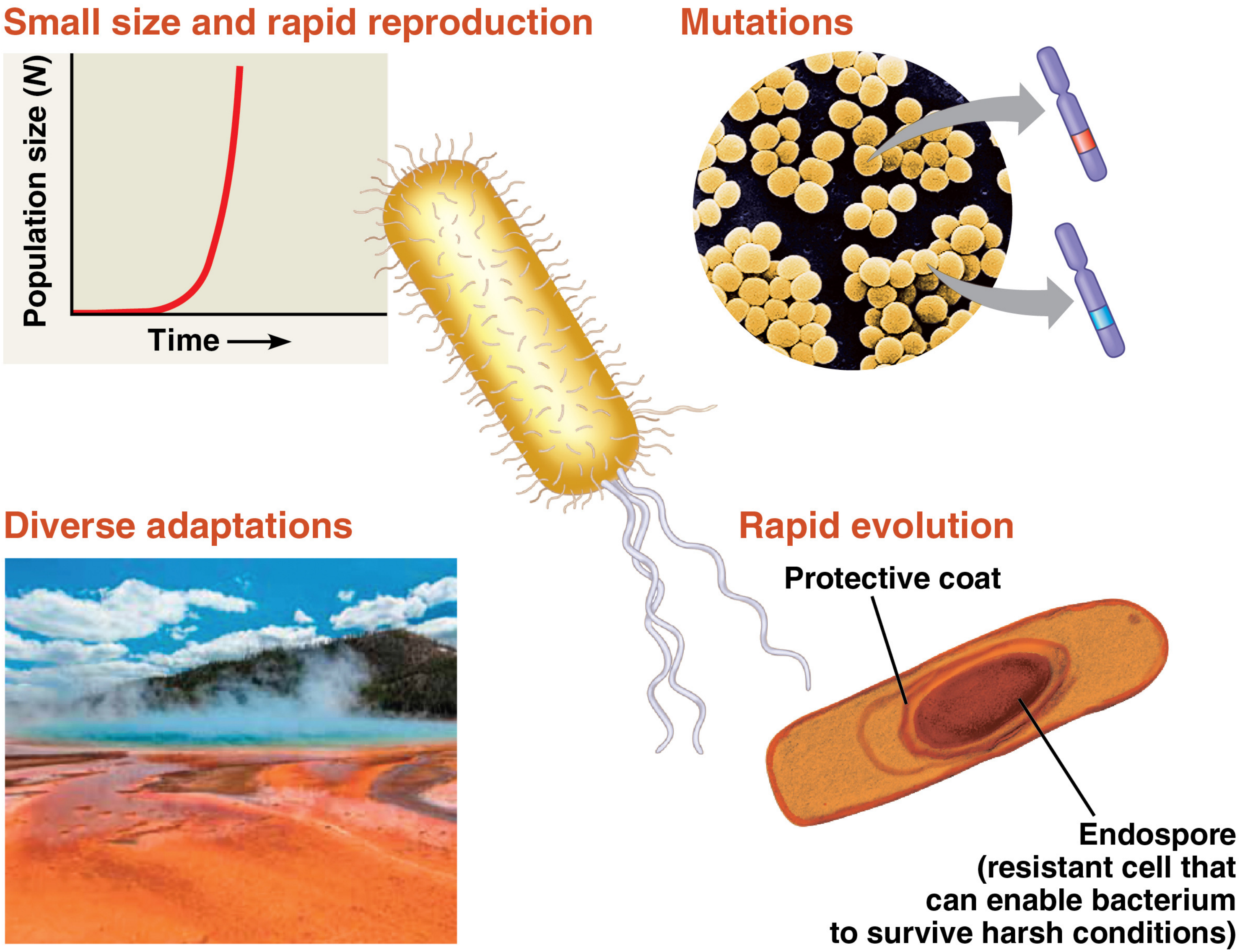
Introduction to prokaryotes

Prokaryotes: masters of adaptation

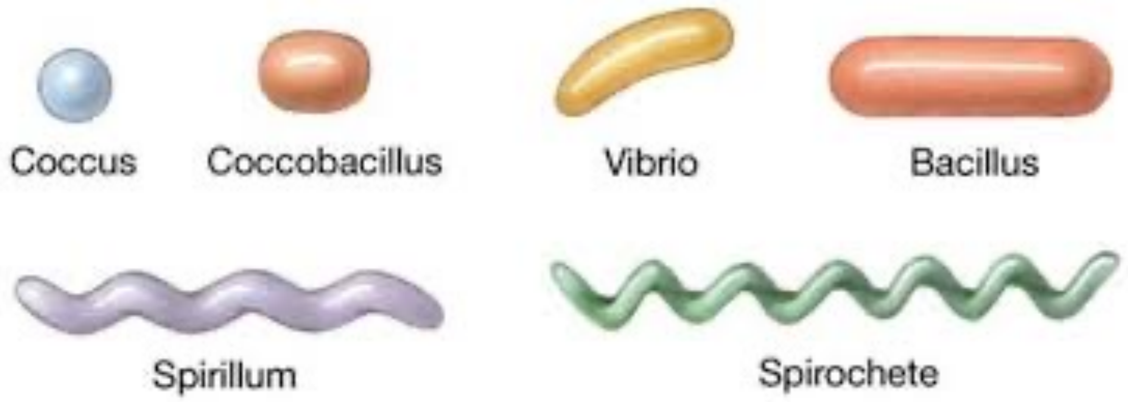
- Prokaryotes thrive almost everywhere, including places too acidic, salty, cold, or hot for most other organisms
- Due to their ability to adapt to diverse habitats, prokaryotes are the most abundant organisms on Earth
- Prokaryotes are divided into two domains: **bacteria** and **archaea**

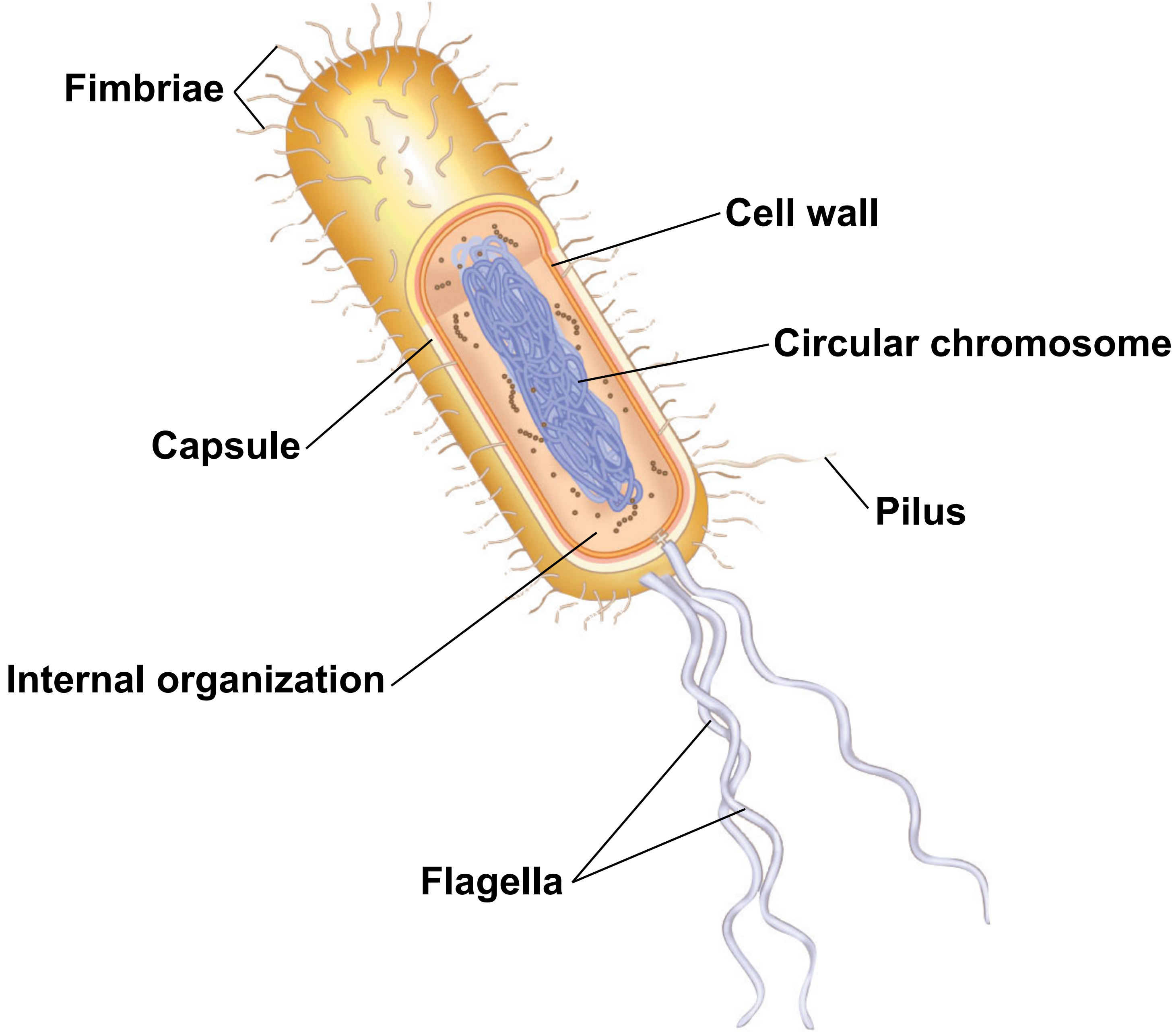
What characteristics enable prokaryotes to reach huge population sizes and thrive in diverse environments?

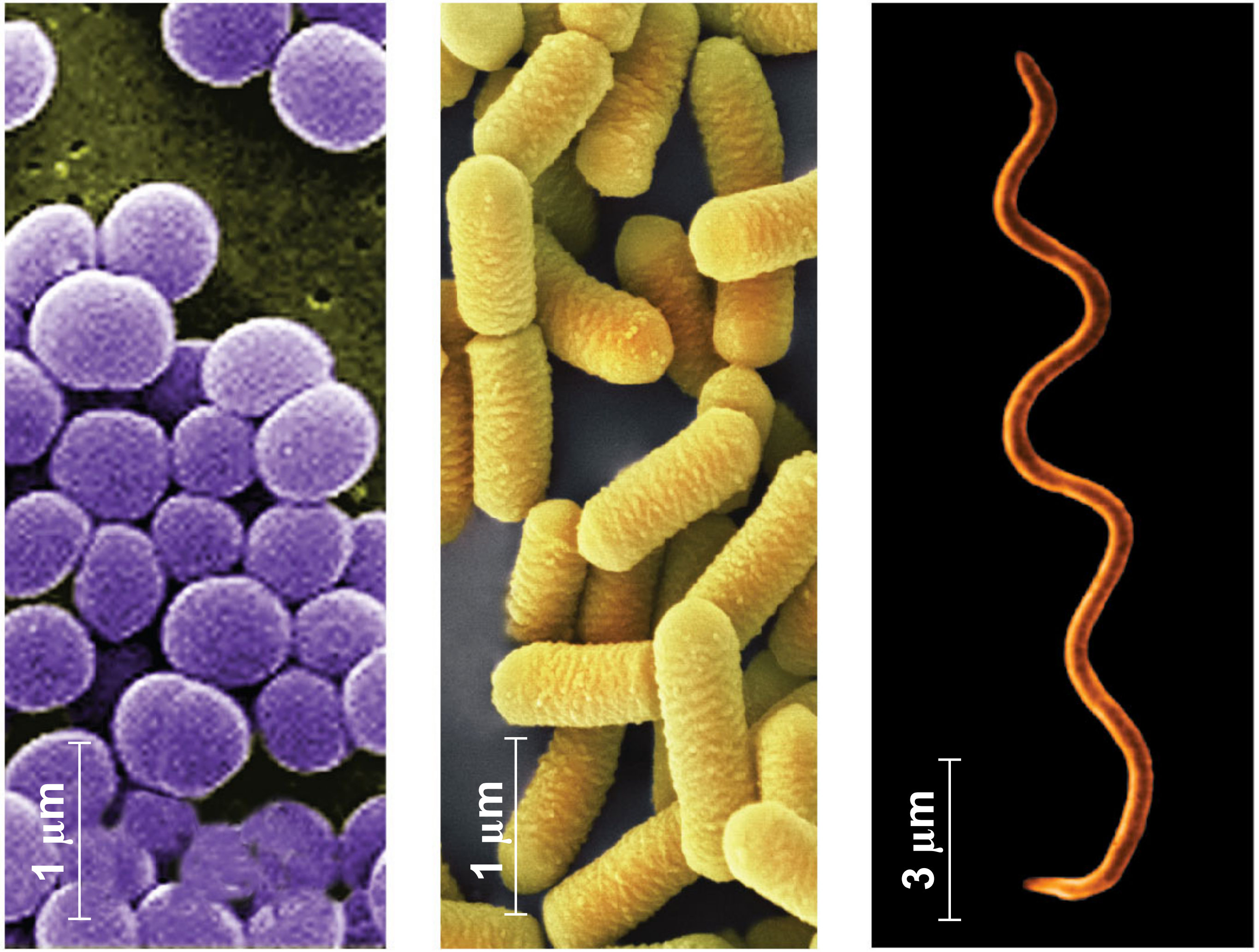


Structural and functional adaptations contribute to prokaryotic success

- Prokaryotes were the first organisms to inhabit the Earth
- Most are unicellular, although some species form colonies
- Most prokaryotic cells are 0.5–5 μm, much smaller than the 10–100 μm of many eukaryotic cells
- Prokaryotic cells have a variety of shapes
- The three most common shapes are spheres (cocci), rods (bacilli), and spirals

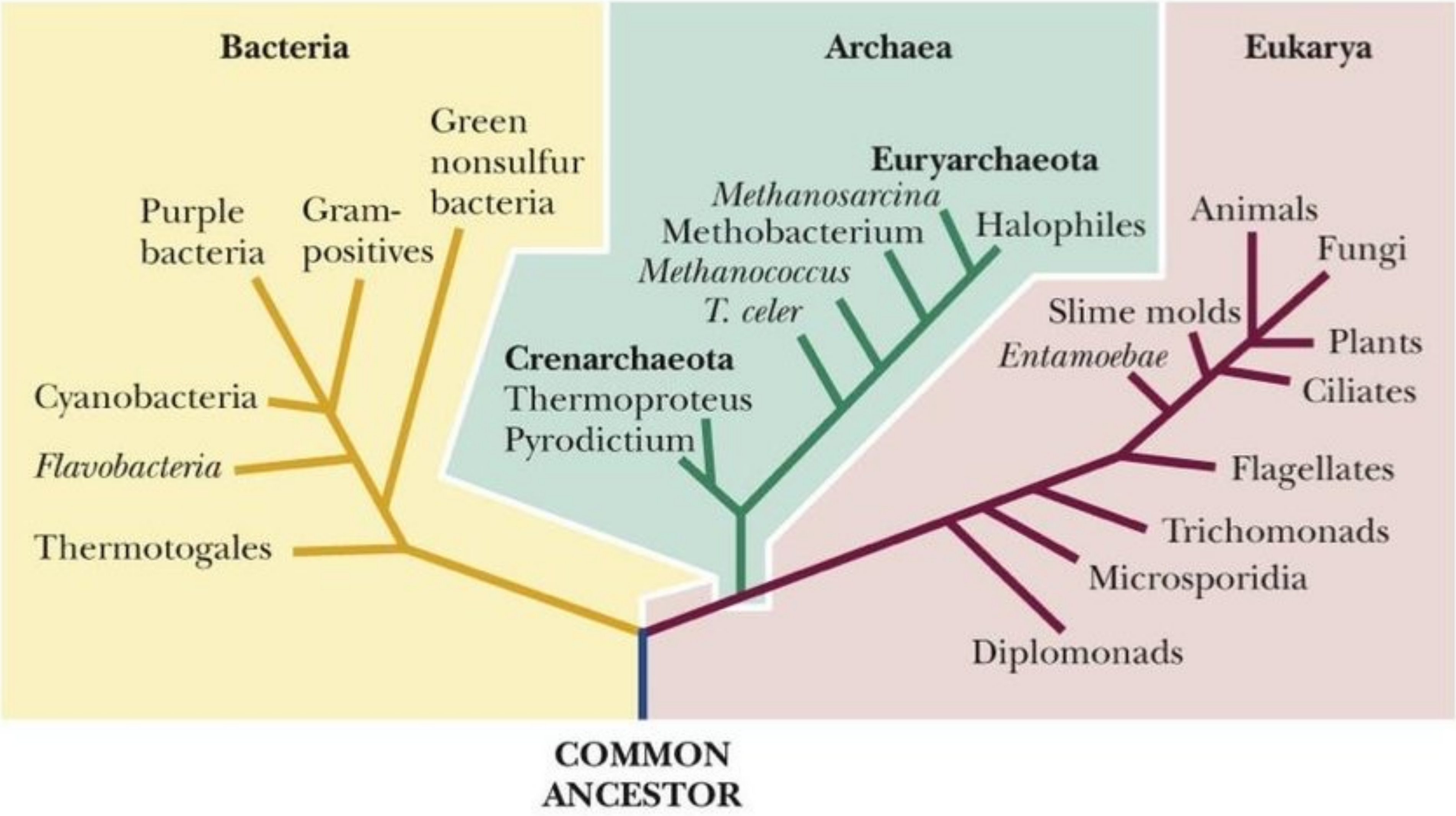



Fimbriae
Cell wall
Circular chromosome
Capsule
Pilus
Internal organization
Flagella



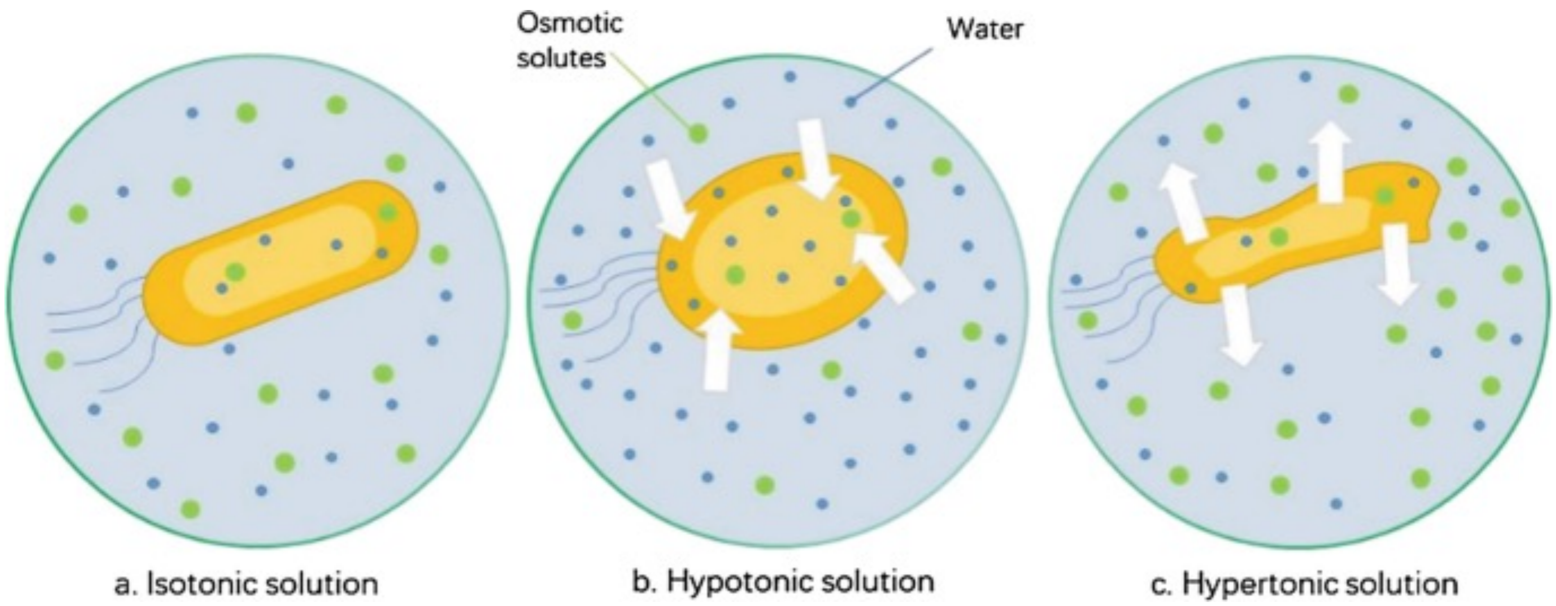
(a) Spherical (b) Rod-shaped (c) Spiral

Three domains of life

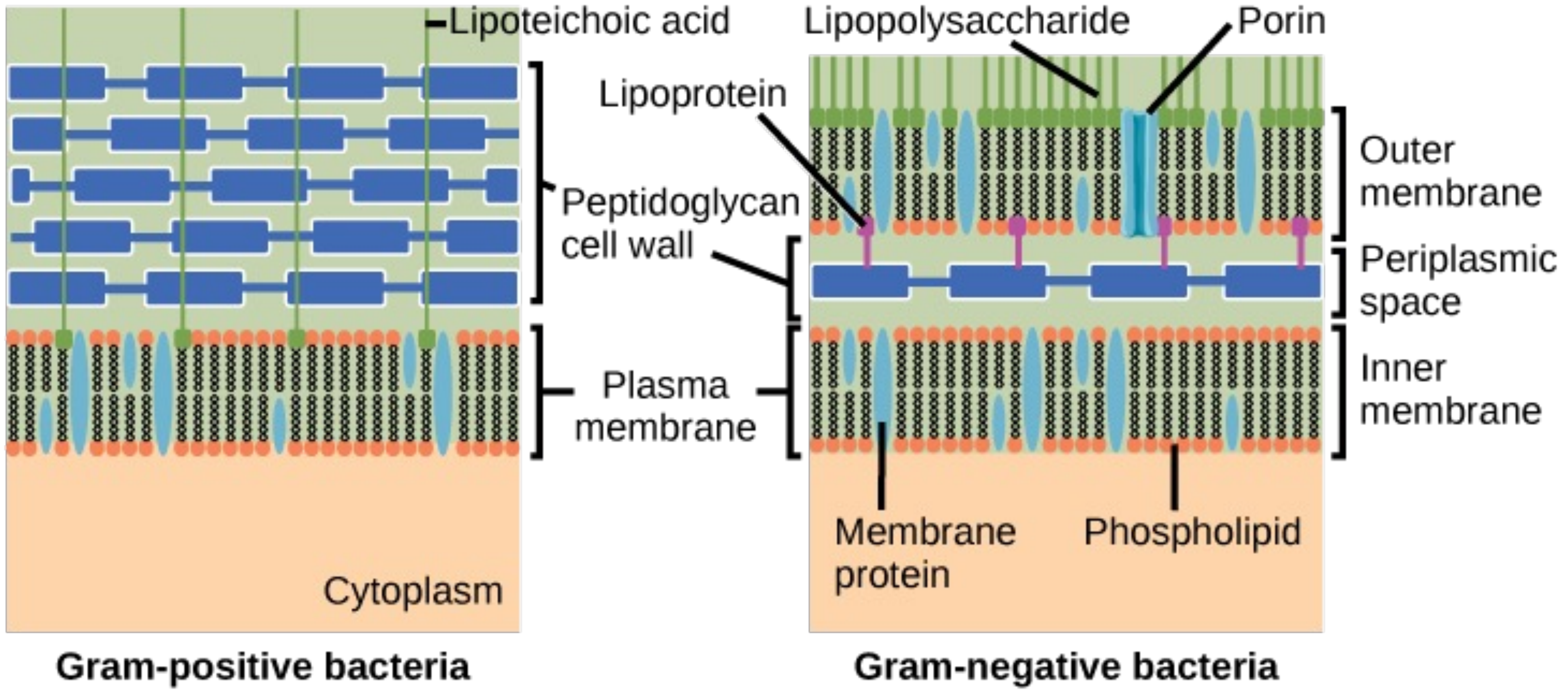


Cell-Surface Structures

- The cell wall maintains cell shape, protects the cell, and prevents it from bursting in a hypotonic environment
- Eukaryote cell walls are made of cellulose or chitin
- Most bacterial cell walls contain **peptidoglycan**, a network of sugar polymers cross-linked by polypeptides

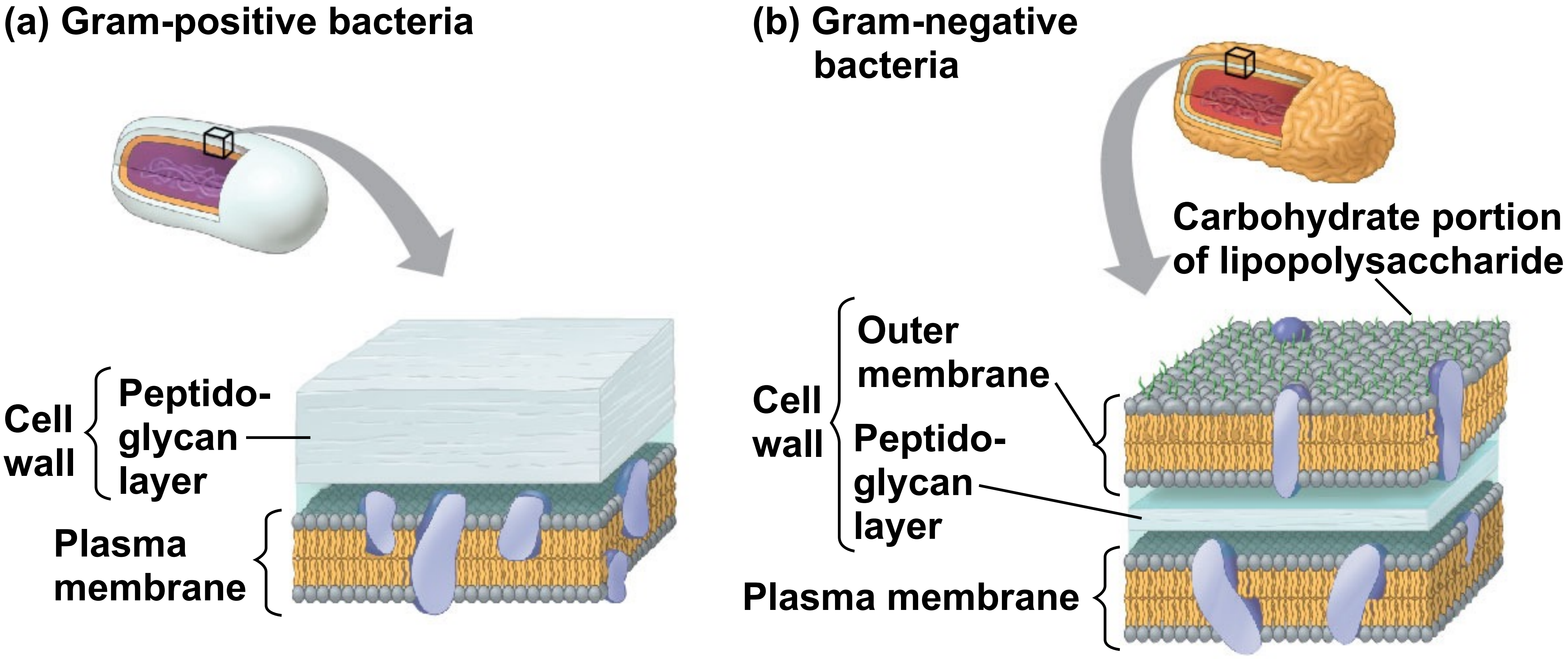


Bacteria cell wall



Bacteria cell wall and Gram stain

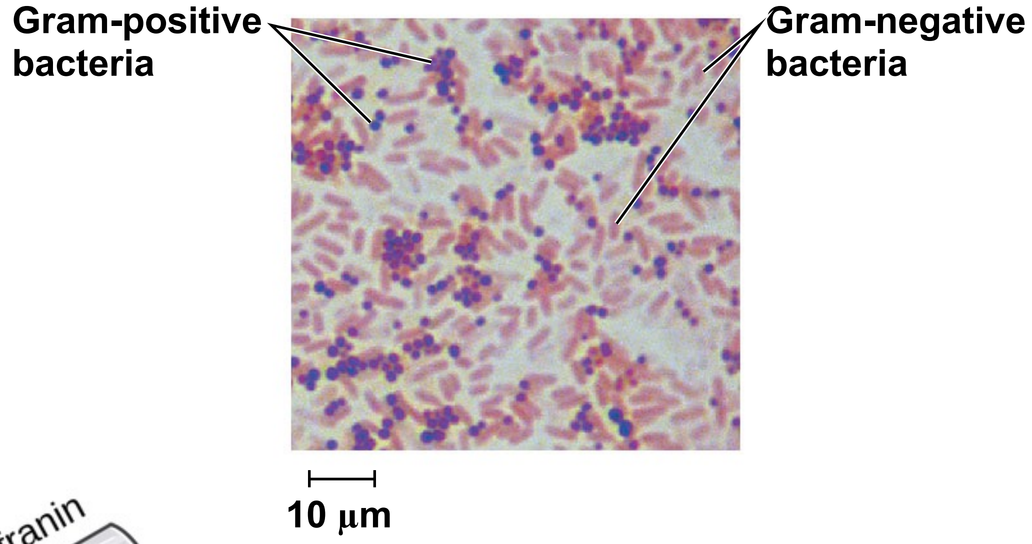
- Archaea contain polysaccharides and proteins but lack peptidoglycan
- Scientists use the **Gram stain** to classify bacteria by cell wall composition
- **Gram-positive** bacteria have simpler walls with a large amount of peptidoglycan
- **Gram-negative** bacteria have less peptidoglycan and an outer membrane that contains lipopolysaccharides
- Many antibiotics target peptidoglycan and damage bacterial cell walls
- Gram-positive bacteria are particularly susceptible to this type of antibiotics

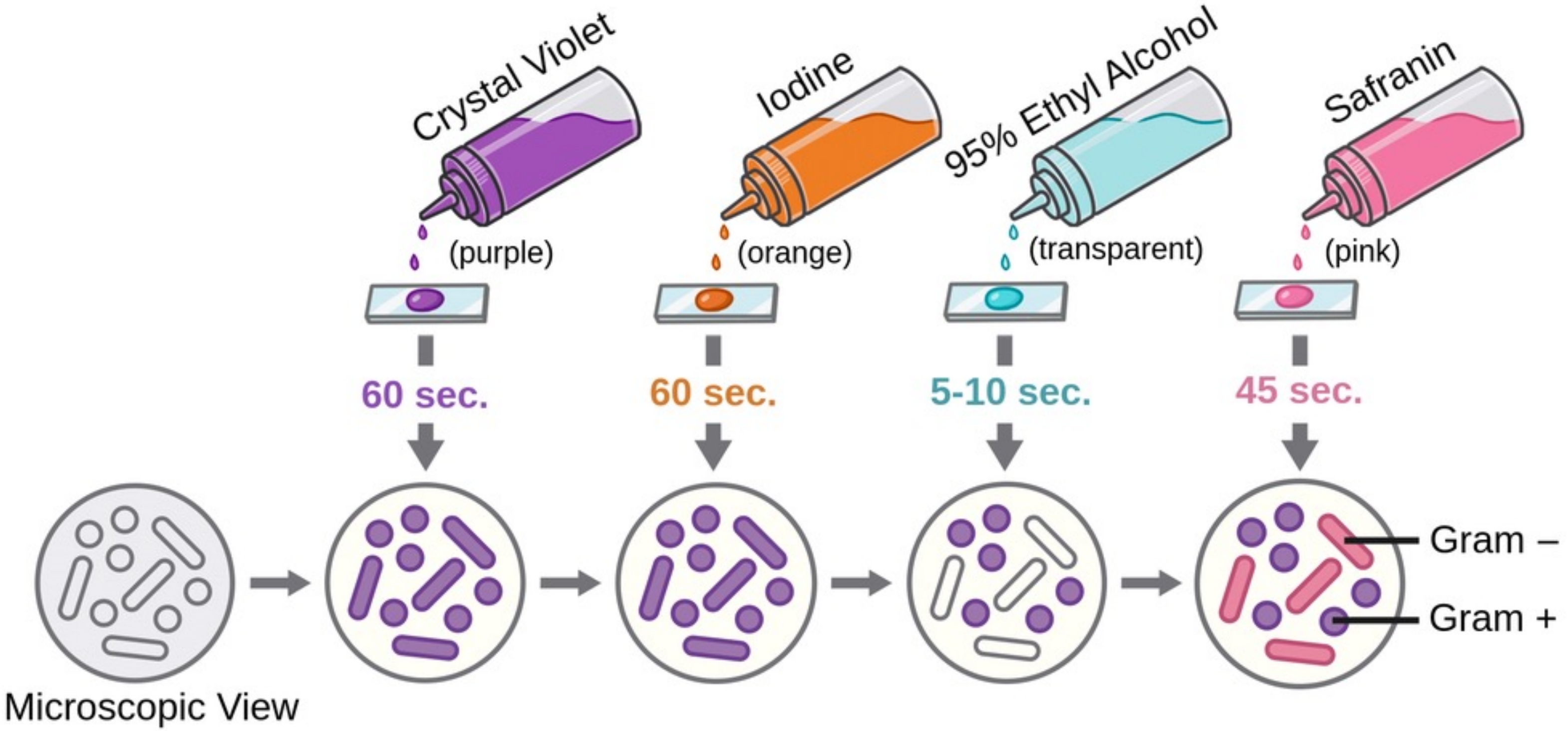


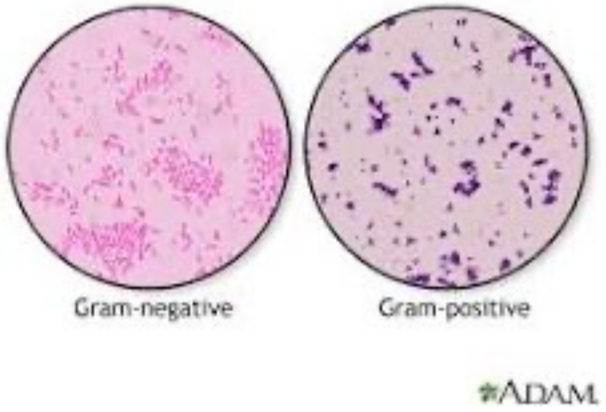
Peptidoglycan traps crystal violet, which masks the red safranin dye.

Crystal violet is easily rinsed away, revealing the red safrinin dye.

Gram stain

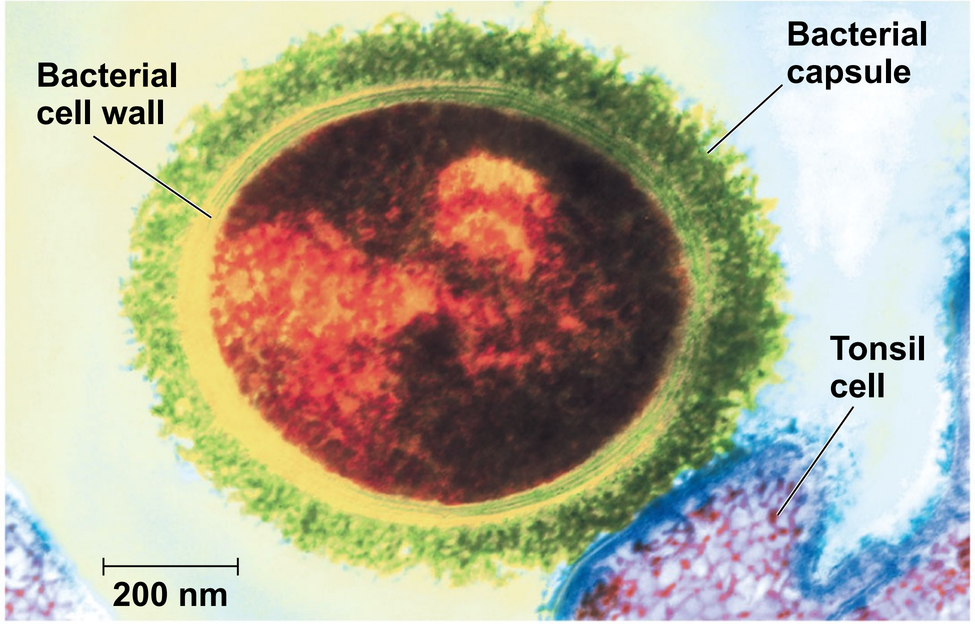

Gram-positive
bacteria
Gram-negative
bacteria
10 µm

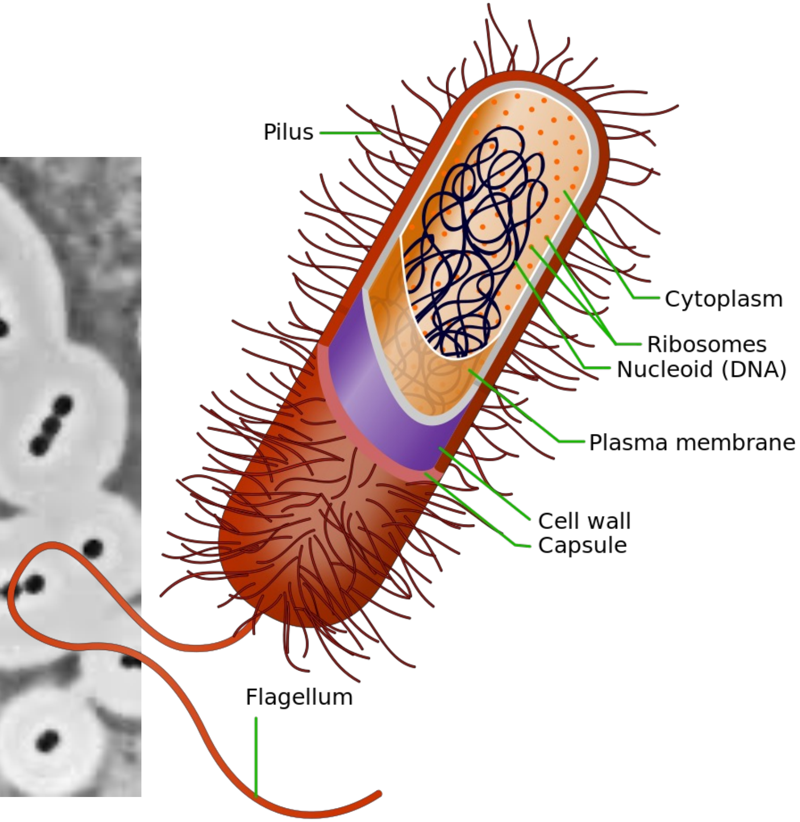

Crystal Violet
(purple)
60 sec.
Iodine
(orange)
60 sec.
95% Ethyl Alcohol
(transparent)
5-10 sec.
Safranin
(pink)
45 sec.
Microscopic View
Gram –
Gram +


Gram-negative
Gram-positive
ADAM

Bacteria capsule

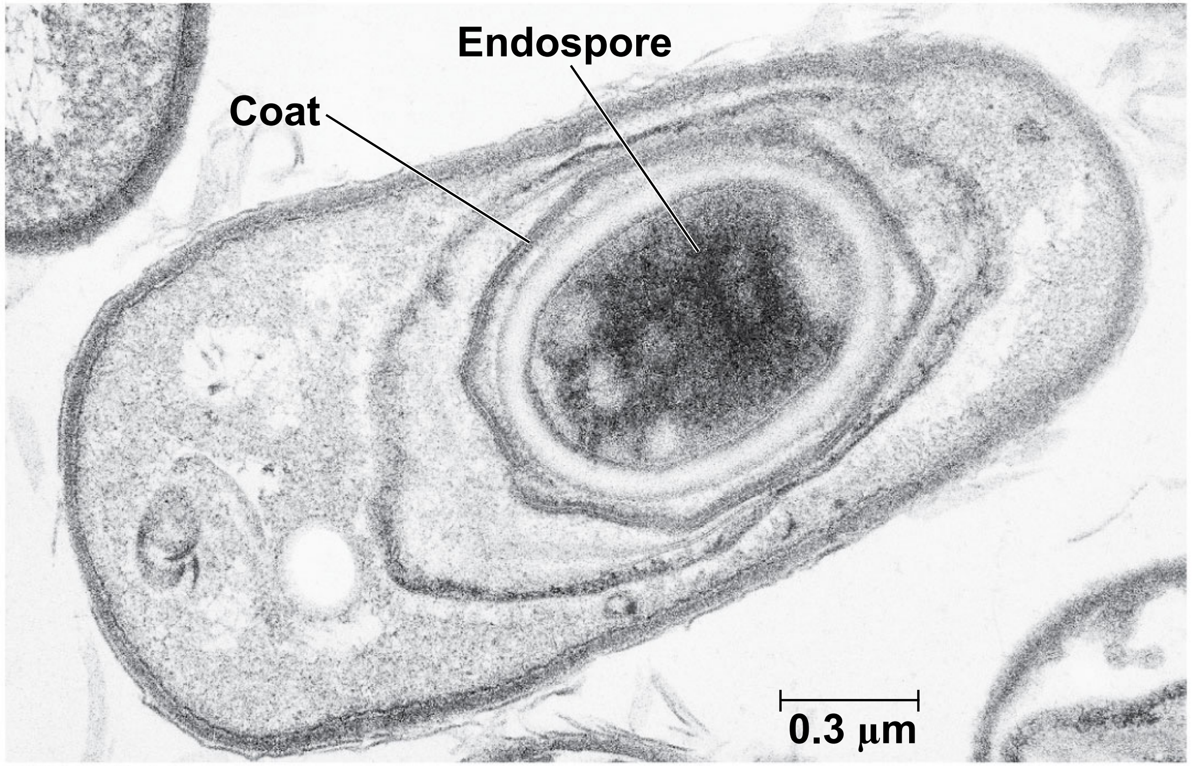
- A sticky outer layer of polysaccharide and or polypeptides called a **capsule** is present in some prokaryotes
- The capsule allows adherence to the substrate, or other individuals, and can shield pathogenic bacteria from the host immune system



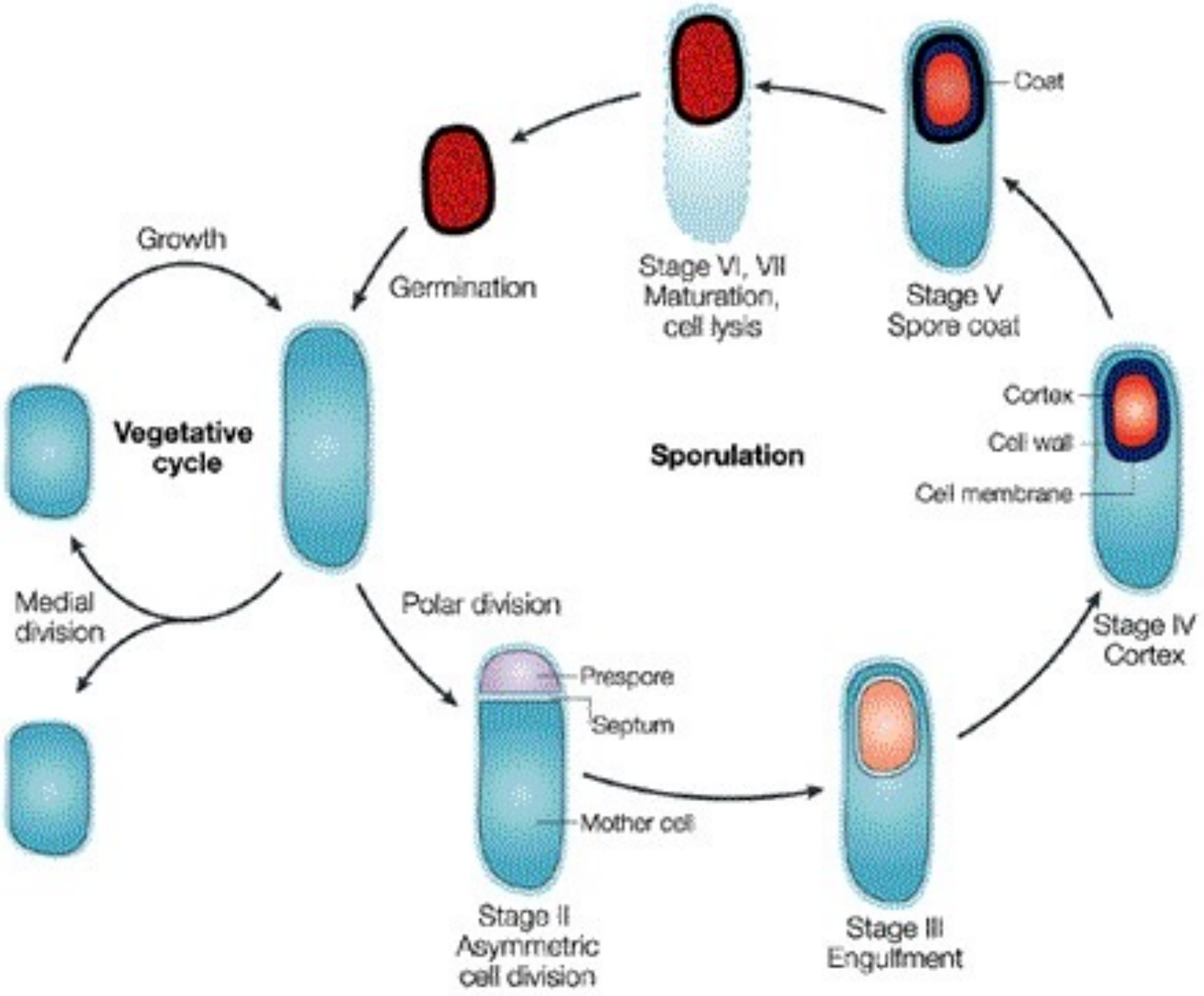


Bacteria endospores

- Many prokaryotes form metabolically inactive **endospores**, which can remain viable in harsh conditions for centuries



Bacteria sporulation



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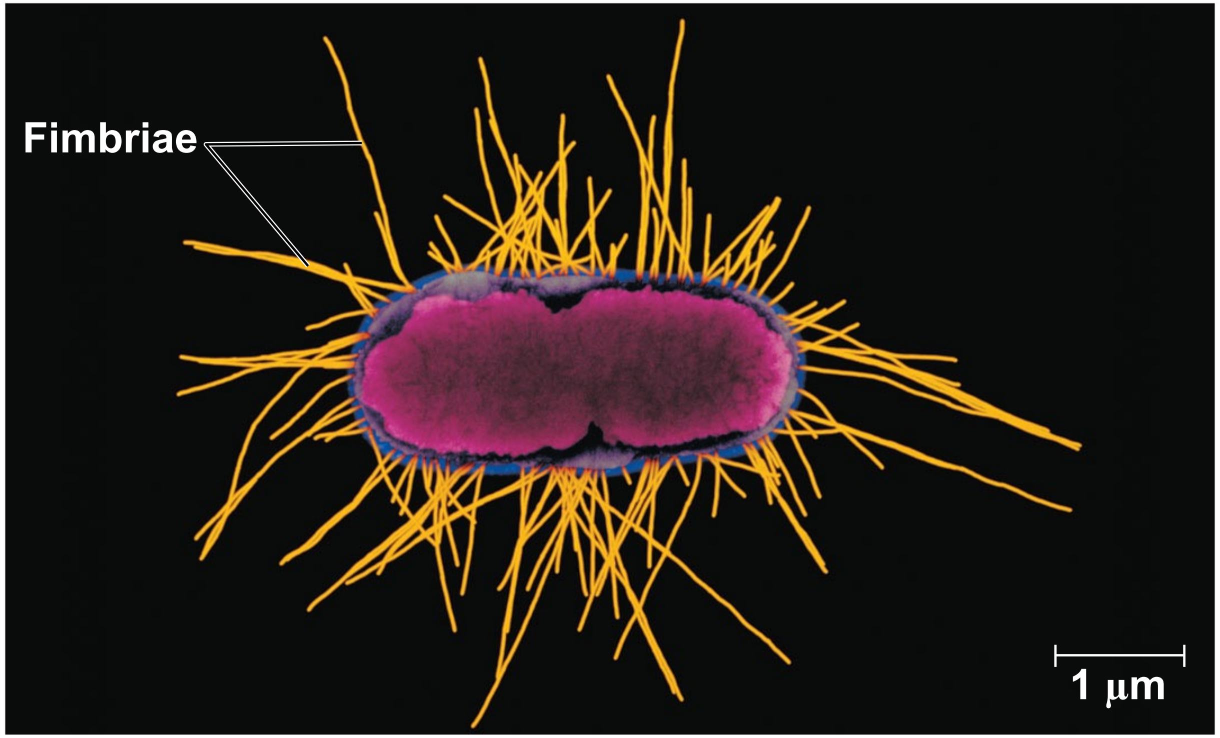
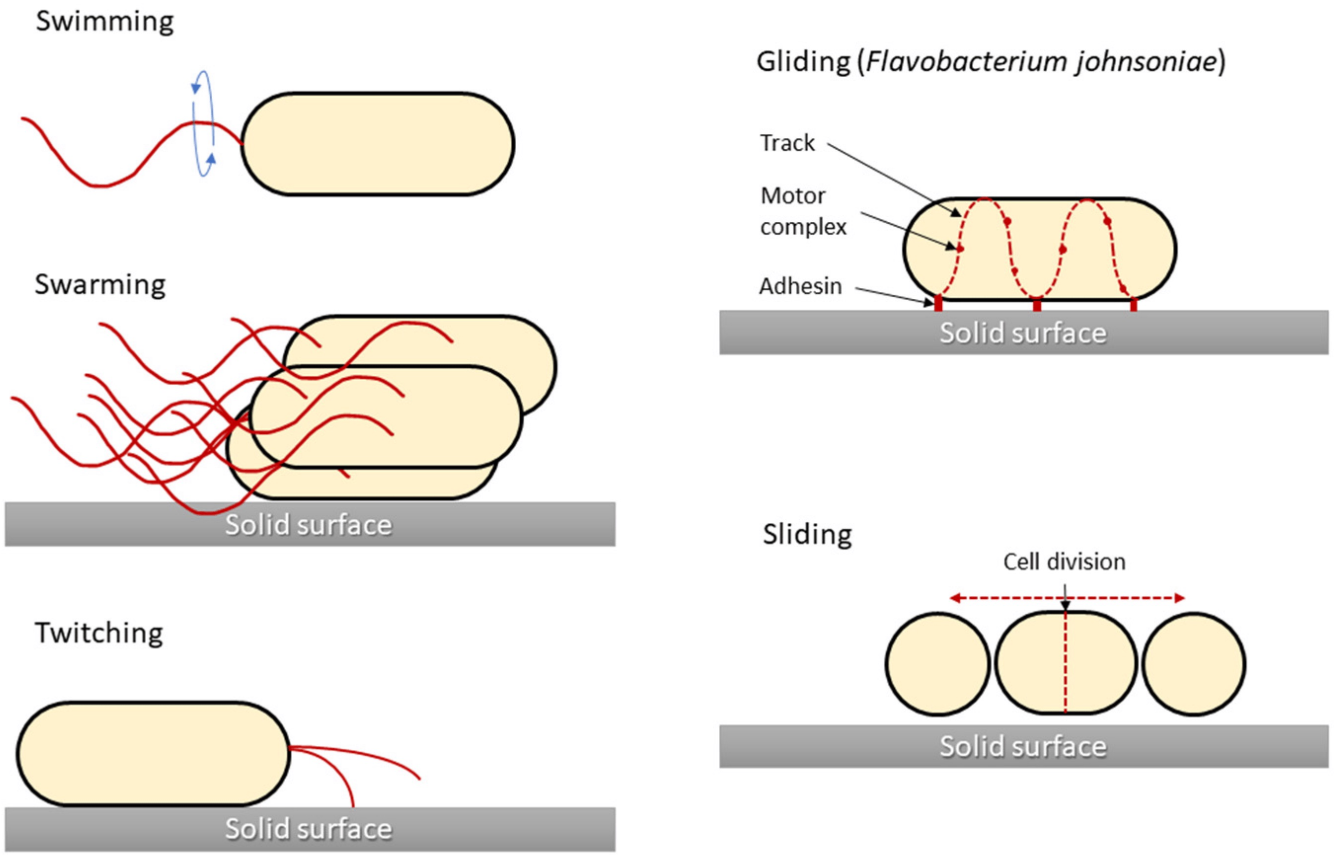
Fimbriae and pili

- Some prokaryotes have hairlike appendages called **fimbriae** that allow them to stick to their substrate or other individuals in a colony
- They play crucial roles in bacterial adhesion, interaction with the environment, and in some cases, motility
- **Pili** (or sex pili) are longer than fimbriae and allow prokaryotes to exchange DNA



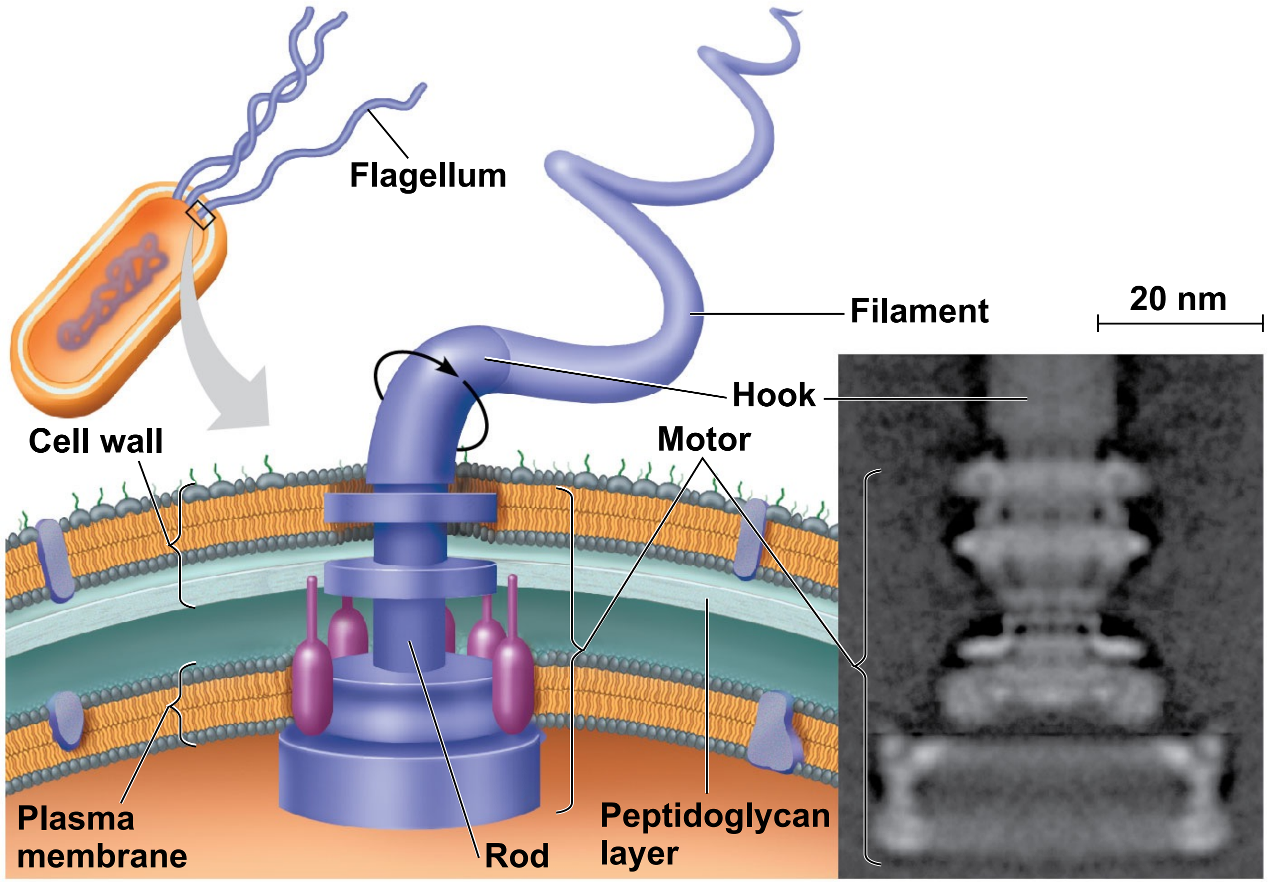
Motility

- About half of all prokaryotes exhibit **taxis**, the ability to move toward or away from a stimulus
  - For example, chemotaxis is the movement toward or away from a chemical stimulus



Flagella

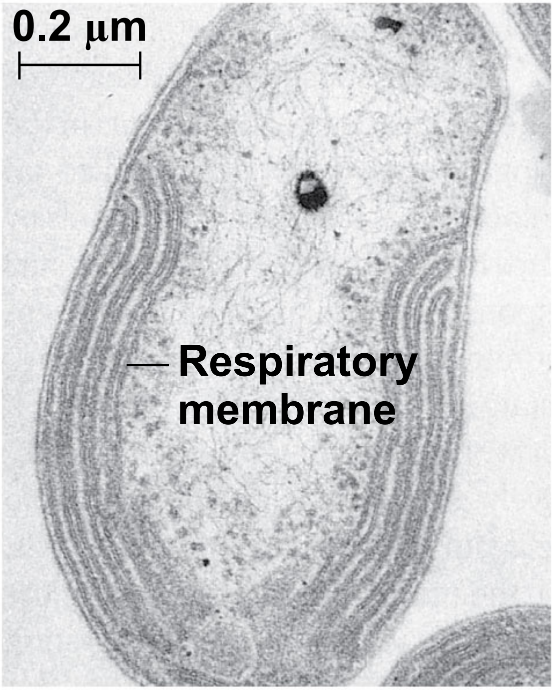
- Flagella are the most common structures used by prokaryotes for movement
- Flagella may be scattered about the surface or concentrated at one or both ends of the cell
- The flagella of prokaryotes and eukaryotes differ in structure, mechanism of propulsion, and molecular composition



Video: Prokaryotic Flagella

Internal Organization and DNA

- Prokaryotic cells usually lack complex compartmentalization
- Some prokaryotes do have specialized membranes that perform metabolic functions
- These are usually infoldings of the plasma membrane



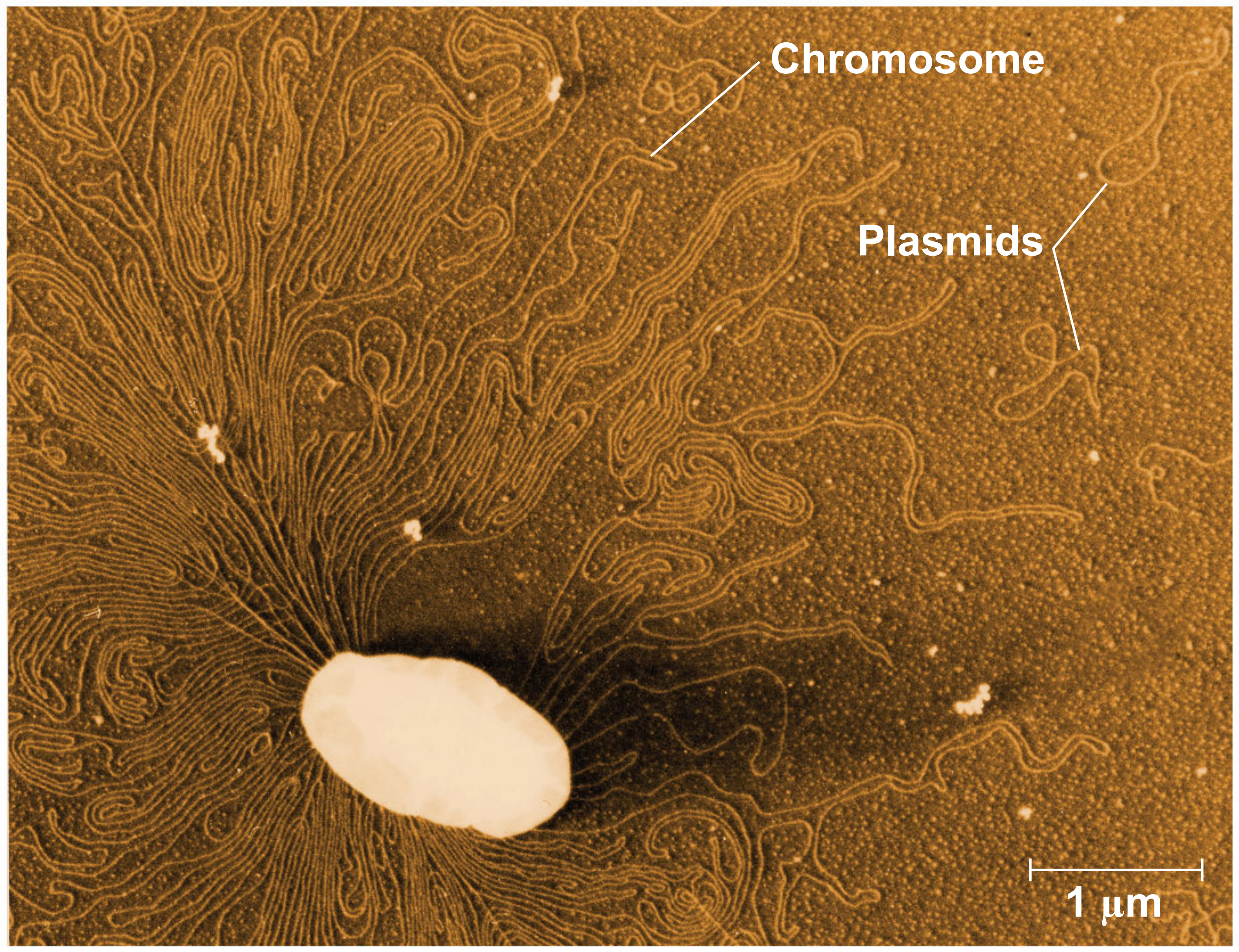
(a) Aerobic prokaryote

(b) Photosynthetic prokaryote

Prokaryote genome

- The prokaryotic genome has less DNA than the eukaryotic genome
- Most of the genome consists of a circular chromosome
- The chromosome is not contained in a nucleus; it is located in the **nucleoid** region with no surrounding membrane
- Typical prokaryotes also have smaller rings of independently replicating DNA called **plasmids**
- There are some differences between prokaryotes and eukaryotes in DNA replication, transcription, and translation
- These differences allow people to use certain antibiotics to inhibit bacterial growth without harming themselves

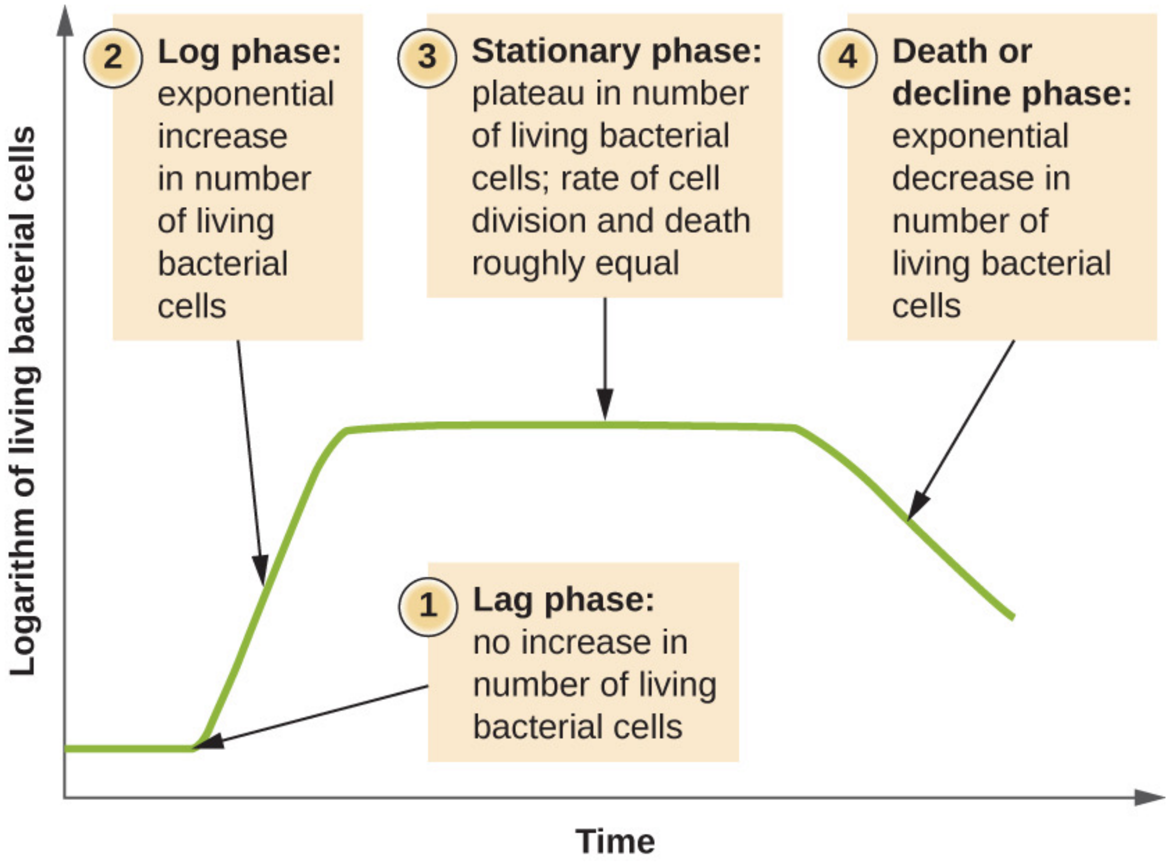
A prokaryotic chromosome and plasmids



Reproduction

- Prokaryotes reproduce quickly by binary fission and can divide every 1–3 hours under optimal conditions
- Key features of prokaryote biology:
    - They are small
    - They reproduce by binary fission
    - They have short generation times

Bacteria growth curve



Rapid reproduction, mutation, and genetic recombination promote **genetic diversity in prokaryotes**

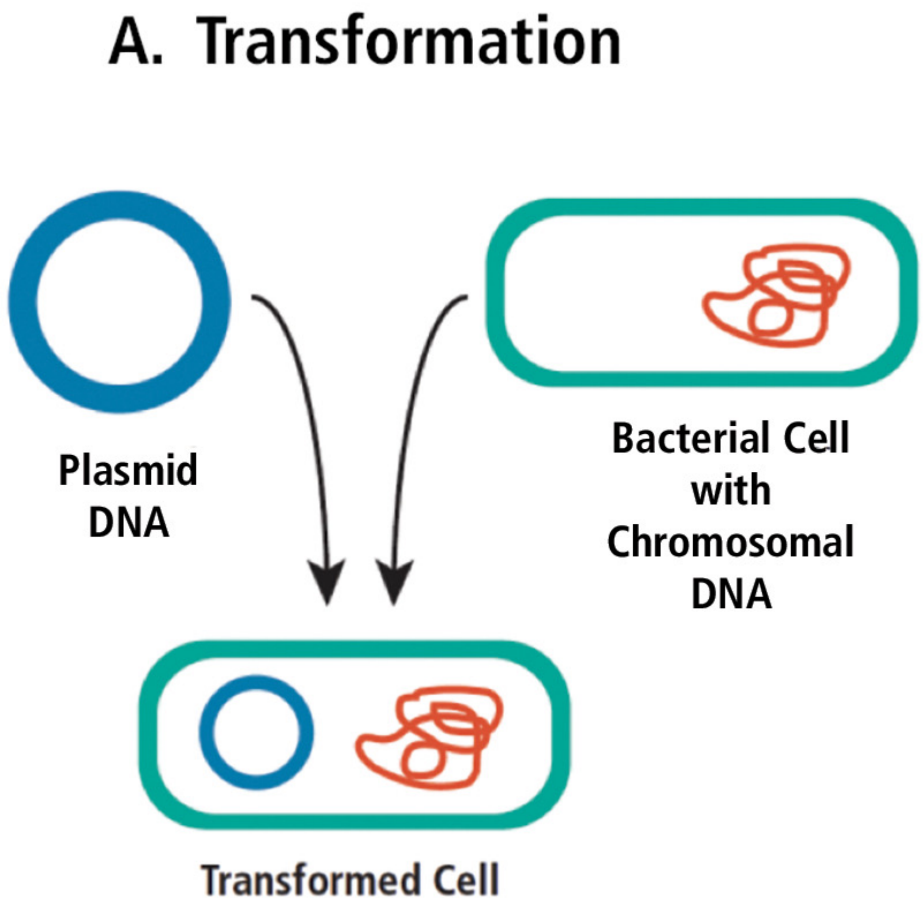
- Prokaryotes have considerable genetic variation
- Three factors contribute to this genetic diversity:
  - Rapid reproduction
  - Mutation
  - Genetic recombination
- Prokaryotes reproduce asexually; offspring cells are generally identical
  - For example, *Escherichia coli* cells reproduce using binary fission
  - Mutation rates are low, but mutations accumulate rapidly because generation times are short and populations are large
- Prokaryotes have simpler cells than eukaryotes, but their rapid adaptation to environmental change indicates that they are highly evolved

Genetic Recombination

- Genetic recombination, the combining of DNA from two sources, contributes to diversity
- Prokaryotic DNA from different individuals can be brought together by transformation, transduction, and conjugation
- Movement of genes among individuals from different species is called horizontal gene transfer

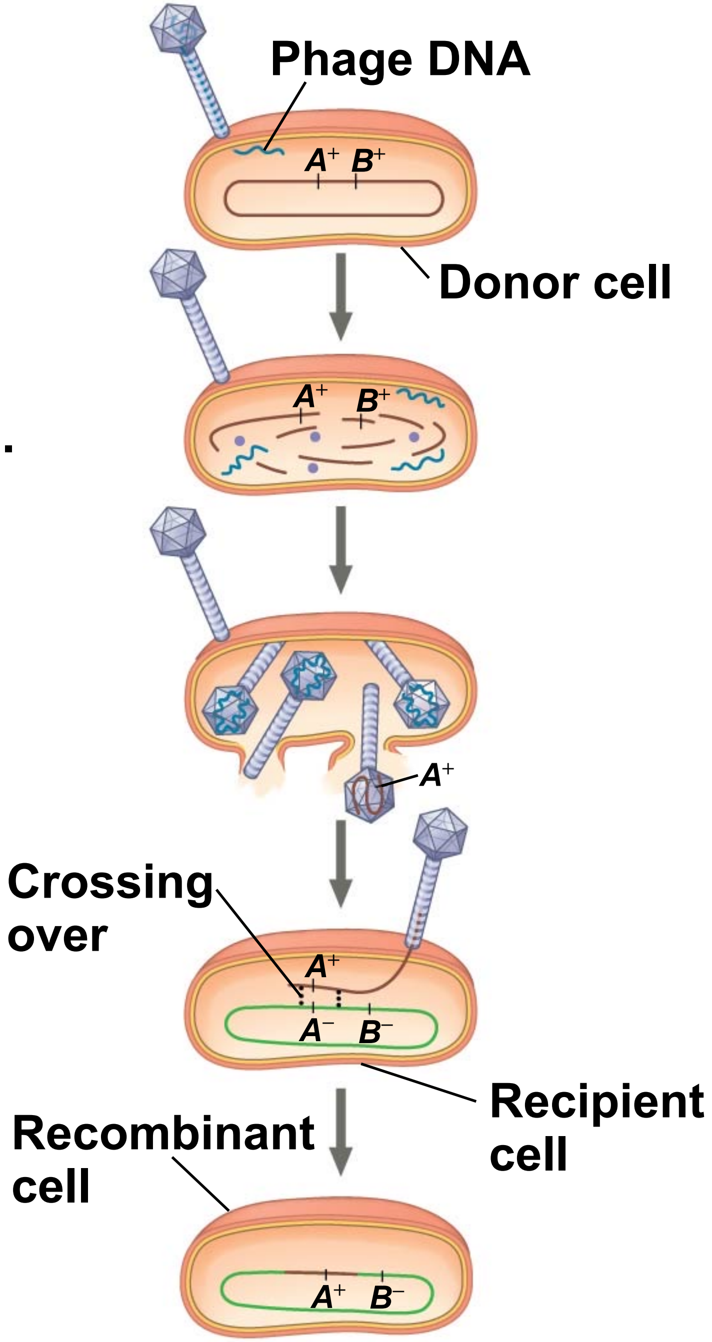
Transformation and Transduction

- A prokaryotic cell can take up and incorporate foreign DNA from the surrounding environment in a process called **transformation**
- **Transduction** is the movement of genes between bacteria by phages (from "bacteriophages," viruses that infect bacteria)



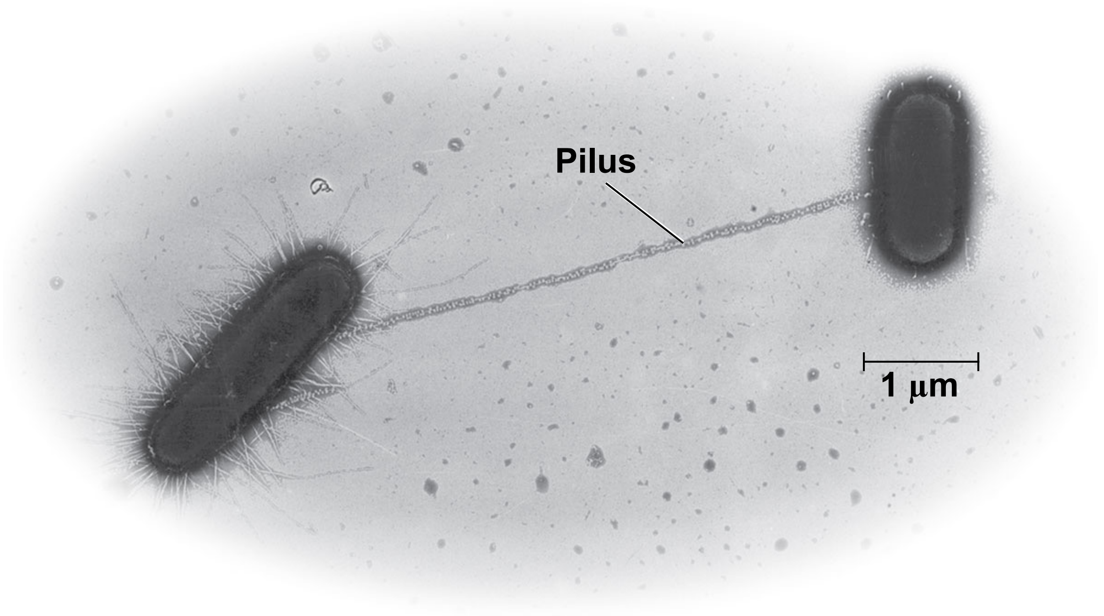
Transduction

1. Phage infects bacterial donor cell that carries the A^+ and B^+ alleles.
2. Phage DNA is replicated and phage proteins are synthesized.
3. Fragment of bacterial DNA with A^+ allele is packaged within a phage capsid.
4. Phage with A^+ allele infects bacterial recipient cell.
5. Incorporation of phage DNA creates recombinant cell with genotype $A^+ B^-$.



Conjugation and Plasmids

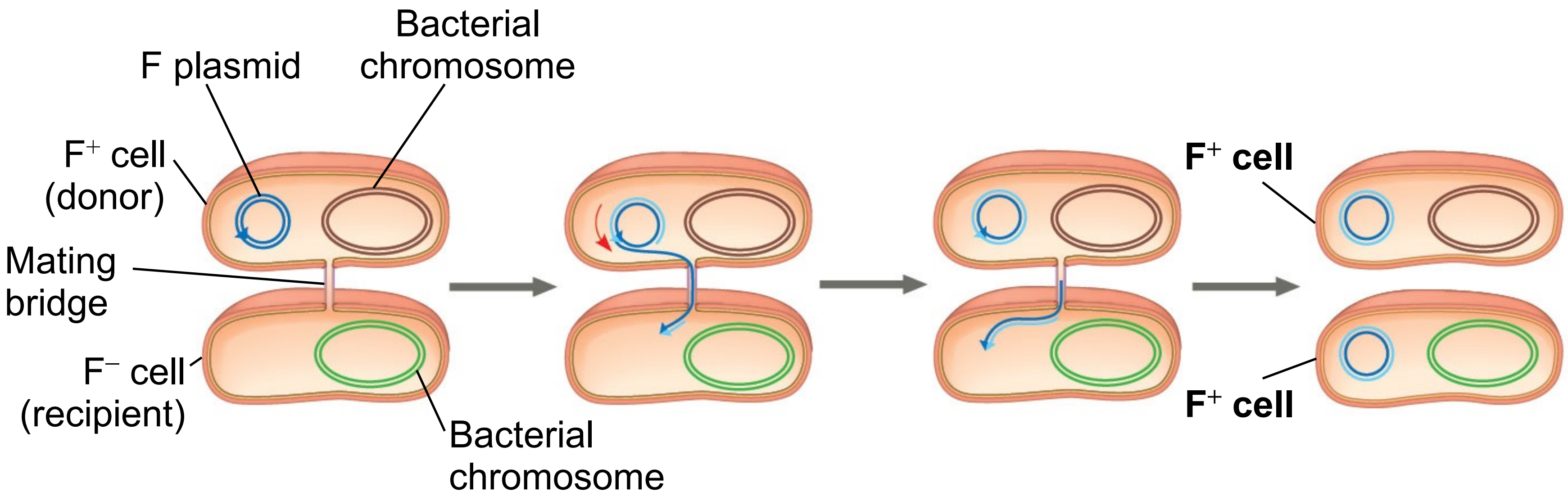
- **Conjugation** is the process where genetic material is transferred between prokaryotic cells
- In bacteria, the DNA transfer is always one way
- A donor cell attaches to a recipient by a pilus, pulls it closer, and transfers DNA through a structure called the “mating bridge”
- A piece of DNA called the **F factor** is required for the production of pili



The F Factor as a Plasmid

- Cells containing the **F plasmid** function as DNA donors during conjugation
- Cells without the F factor function as DNA recipients during conjugation
- The F factor is transferable during conjugation
- Provided some of the F plasmid's DNA is transferred, the recipient cell becomes a recombinant cell

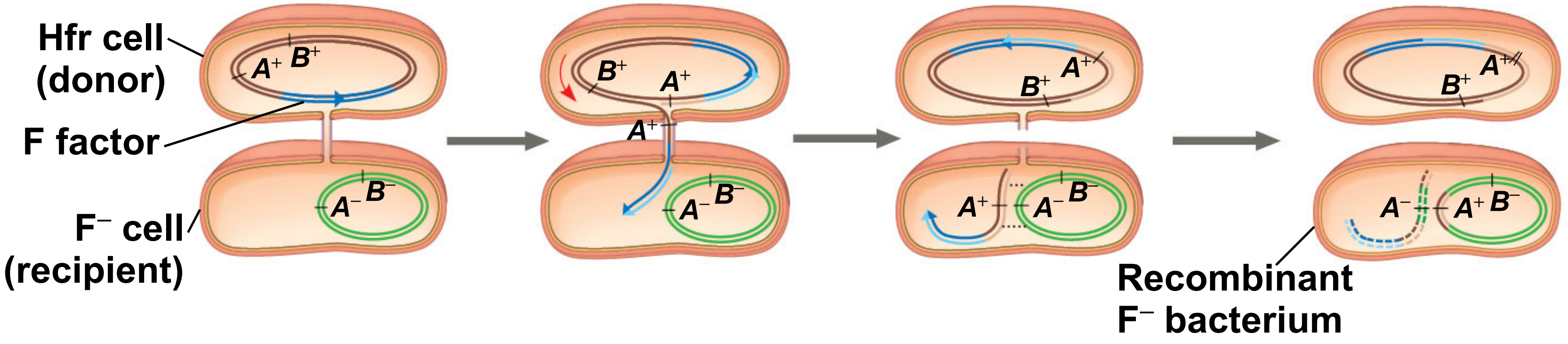
(a) Conjugation and transfer of an F plasmid



The F Factor in the Chromosome

- A cell with the F factor built into its chromosome functions as a donor during conjugation
- Such cells are called Hfr cells (for *h*igh *f*requency of *r*ecombination)
- The recipient becomes a recombinant bacterium, with DNA from two different cells

Conjugation and transfer of part of an Hfr bacterial chromosome, resulting in recombination



1. An Hfr cell forms a mating bridge with an F^- cell.
2. A single strand of the F factor breaks and begins to move through the bridge.
3. Crossing over can result in exchange of homologous genes.
4. Enzymes degrade any DNA not incorporated. Recipient cell is now a recombinant F^- cell.

R Plasmids and Antibiotic Resistance

- **R plasmids** carry genes for antibiotic resistance
- Antibiotics kill sensitive bacteria, but not bacteria with specific R plasmids
- Through natural selection, the fraction of bacteria with genes for resistance increases in a population exposed to antibiotics
- Many R plasmids have genes that encode pili, making it possible for resistance genes to be transferred between bacterial cells
- Some R plasmids carry genes for resistance to multiple antibiotics
- Antibiotic-resistant strains of bacteria are becoming more common, and the infections they cause are now harder to treat

Diverse nutritional and metabolic adaptations have evolved in prokaryotes

- Prokaryotes can be categorized by how they obtain energy and carbon.
- Energy and carbon sources are combined to give four major modes of nutrition:
  - Photoautotroph
  - Chemoautotroph
  - Photoheterotroph
  - Chemoheterotroph

A Nutritional Classification of Organisms

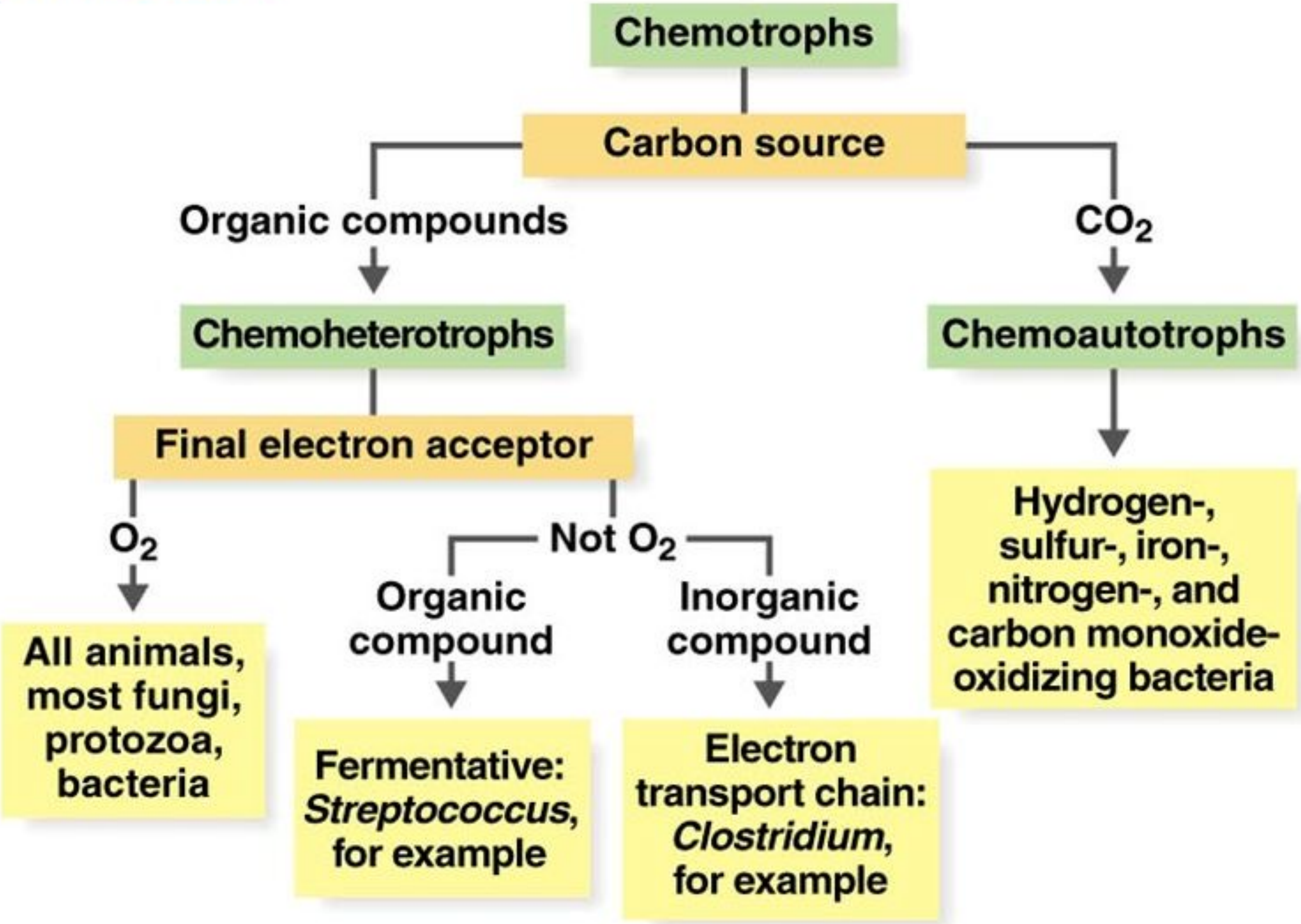


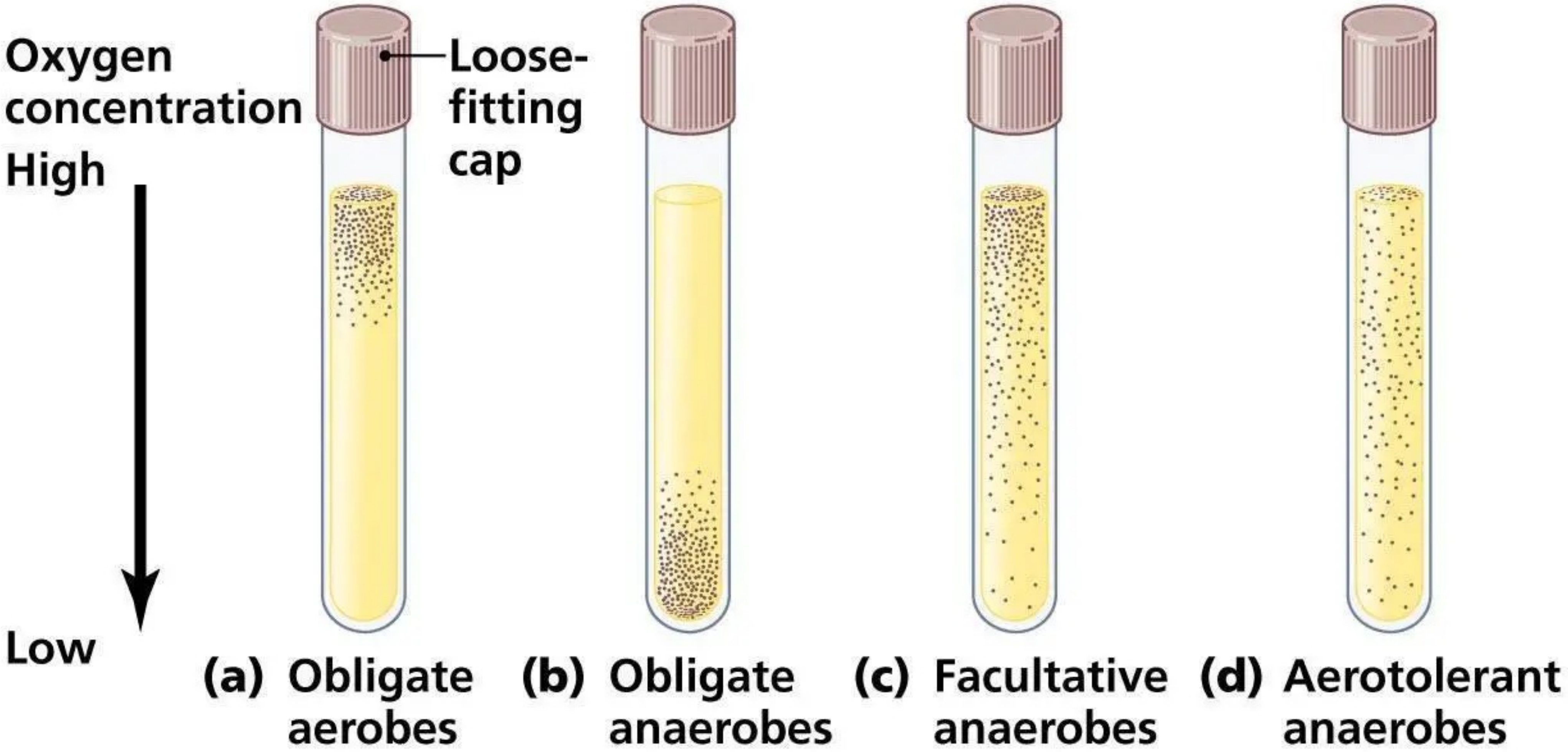
Table 27.1 Major Nutritional Modes

Mode	Energy Source	Carbon Source	Types of Organisms
AUTOTROPH			
Photoautotroph	Light	CO_2, HCO_3^-, or related compound	Photosynthetic prokaryotes (for example, cyanobacteria); plants; certain protists (for example, algae)
Chemoautotroph	Inorganic chemicals (such as H_2S, NH_3, or Fe^{2+})	CO_2, HCO_3^-, or related compound	Unique to certain prokaryotes (for example, *Sulfolobus*)
HETEROTROPH			
Photoheterotroph	Light	Organic compounds	Unique to certain aquatic and salt-loving prokaryotes (for example, *Rhodobacter, Chloroflexus*)
Chemoheterotroph	Organic compounds	Organic compounds	Many prokaryotes (for example, *Clostridium*) and protists; fungi; animals; some plants

The Role of Oxygen in Metabolism

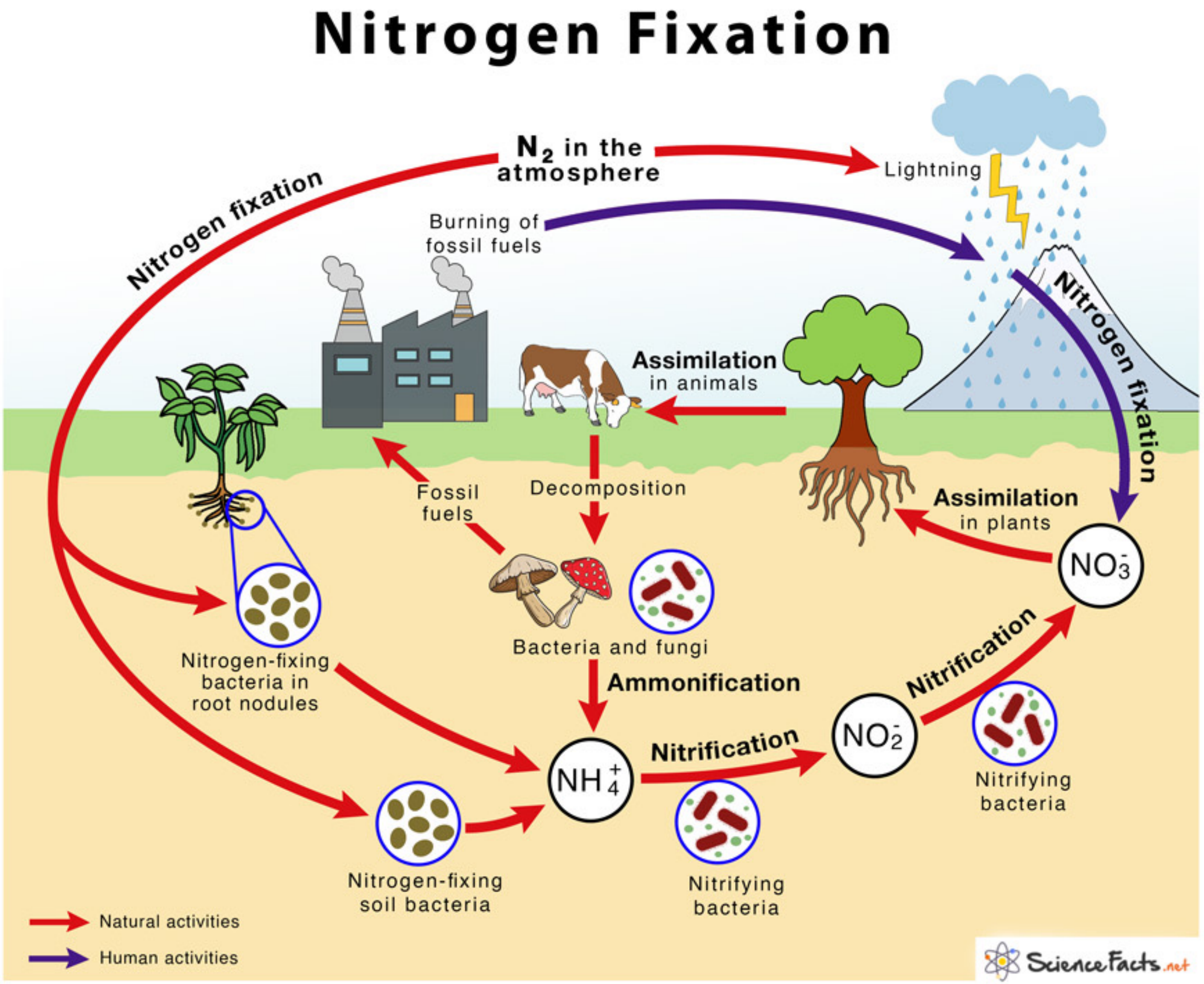
- Prokaryotic metabolism varies with respect to O_2
  - **Obligate aerobes** require O_2 for cellular respiration
  - **Obligate anaerobes** are poisoned by O_2 and live by fermentation or use substances other than O_2 for **anaerobic respiration**
  - **Facultative anaerobes** can use O_2 if it is present or carry out fermentation or anaerobic respiration if it is not

Growth location based on oxygen concentrations



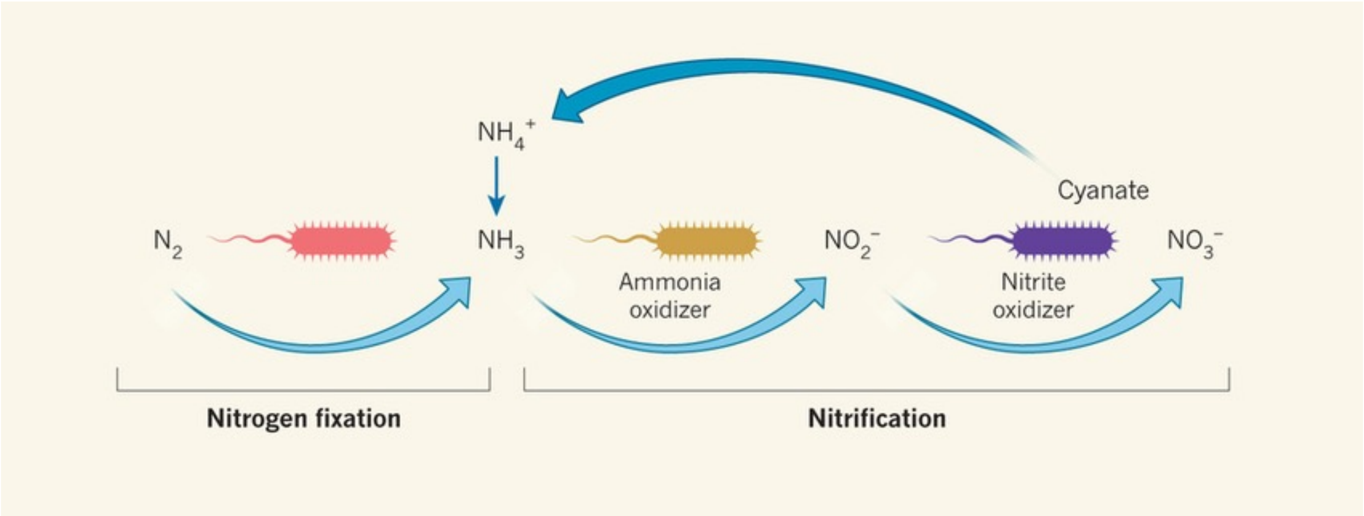
Nitrogen Metabolism

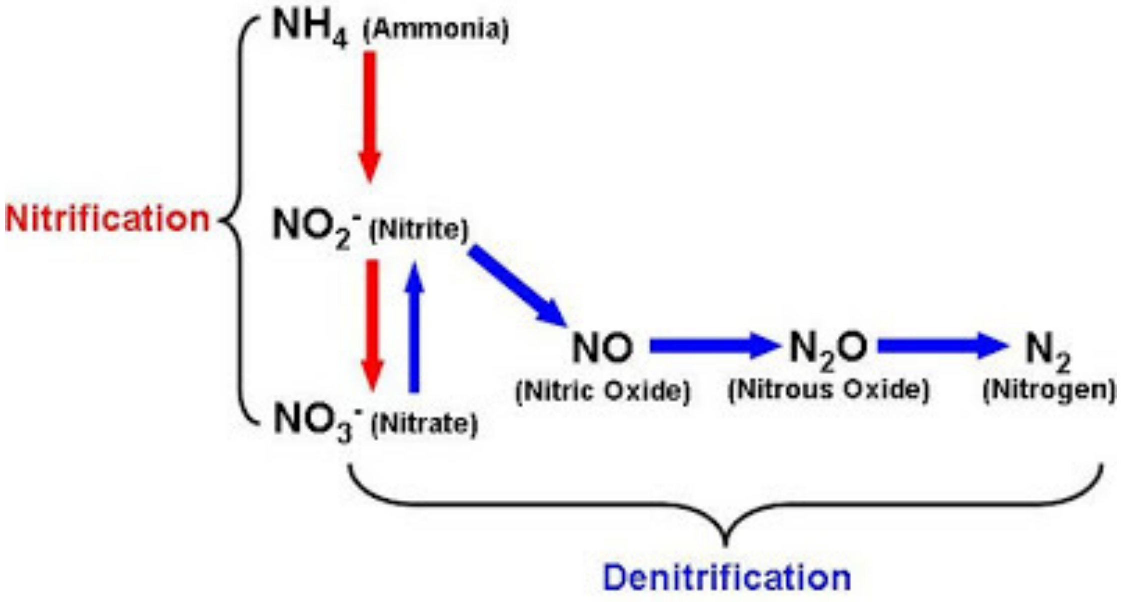
- Nitrogen is essential for the production of amino acids and nucleic acids in all organisms



Nitrogen Metabolism

- Prokaryotes can metabolize nitrogen in a variety of ways
  - For example, some prokaryotes convert atmospheric nitrogen (N_2) to ammonia (NH_3) in a process called **nitrogen fixation**

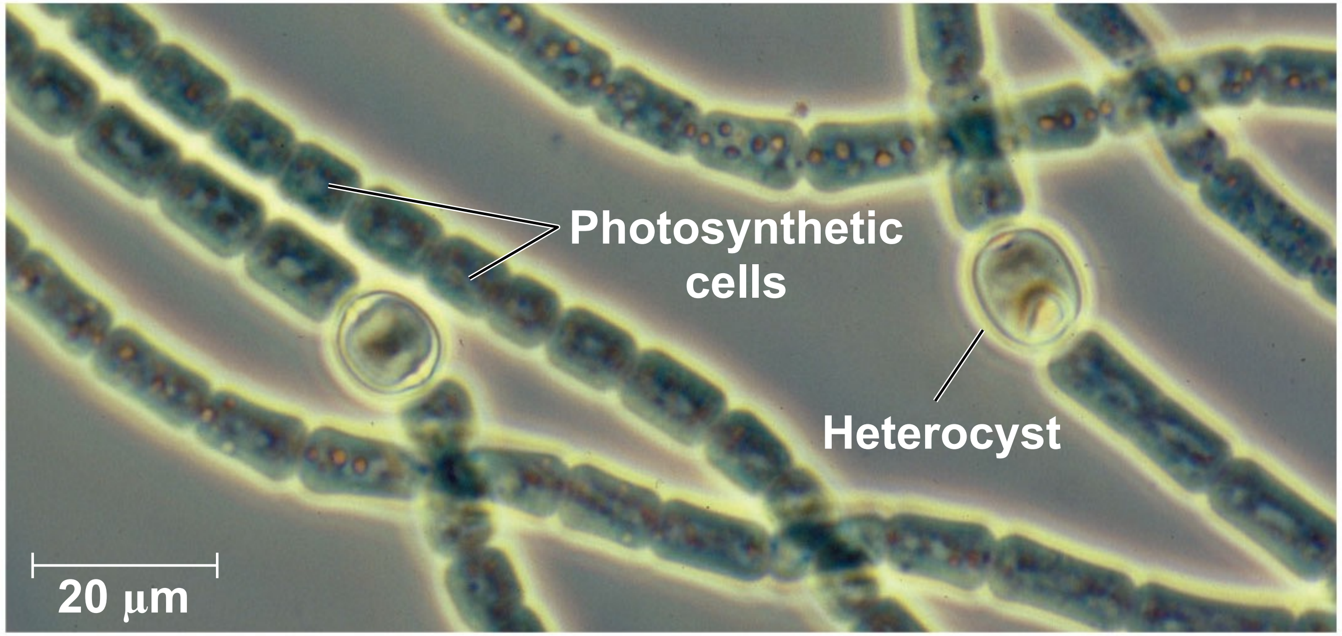




Metabolic Cooperation

- Cooperation between prokaryotes allows them to use environmental resources they could not use as individual cells
- In the cyanobacterium *Anabaena*, photosynthetic cells and nitrogen-fixing cells called **heterocysts** (or heterocytes) exchange metabolic products

- Metabolic cooperation occurs between different prokaryotic species in surface-coating colonies called **biofilms**
- Sulfate-consuming bacteria and methane-consuming bacteria on the ocean floor use each other's waste products



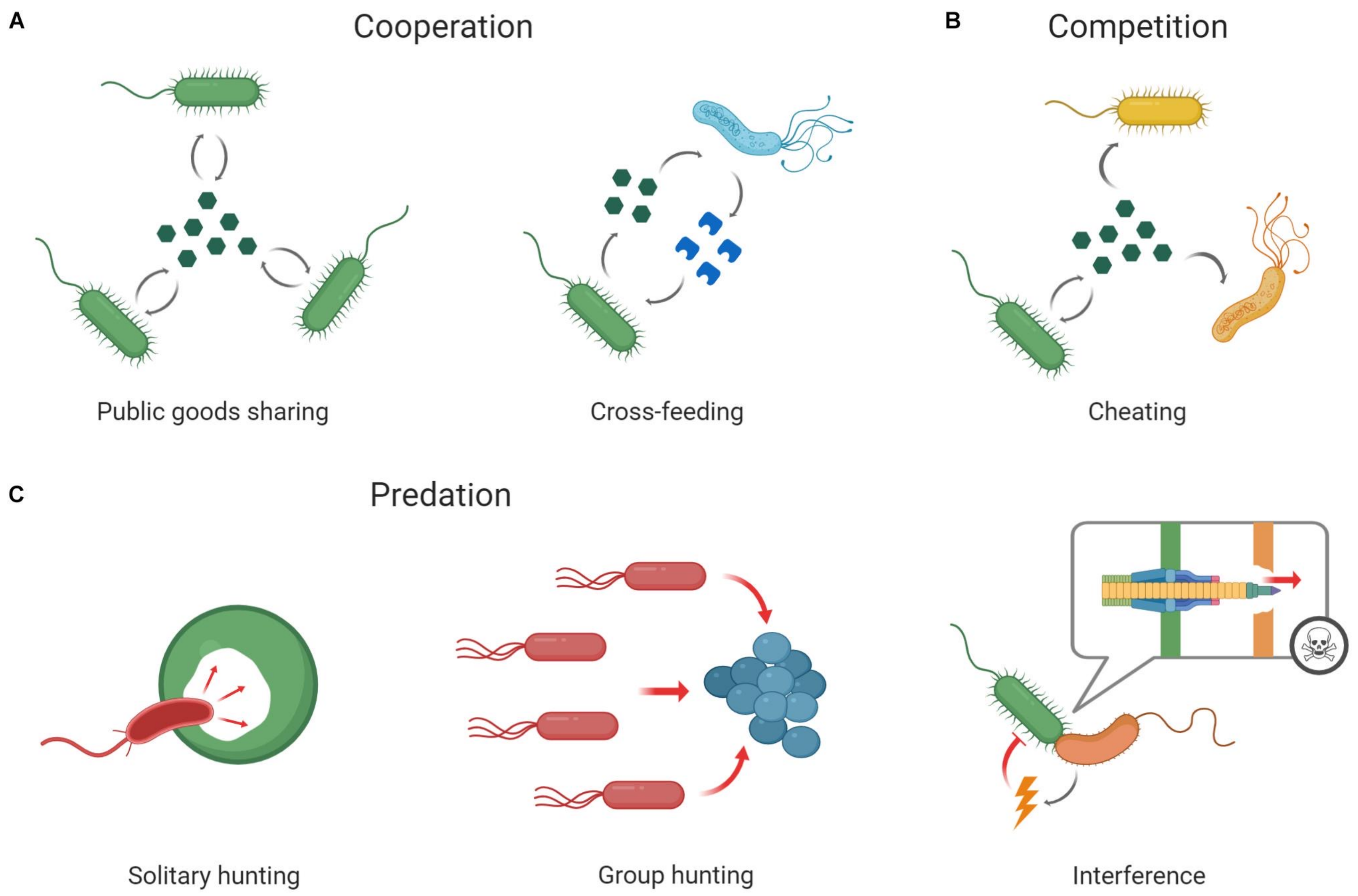
Ecological Interactions

- **Symbiosis** is an ecological relationship in which two species live in close contact: a larger **host** and smaller **symbiont**
- Prokaryotes often form symbiotic relationships with larger organisms

- In **mutualism**, both symbiotic organisms benefit
- In **commensalism**, one organism benefits while neither harming nor helping the other in any significant way
- In **parasitism**, an organism called a **parasite** harms but does not kill its host
- Parasites that cause disease are called **pathogens**

The existence of some ecosystems depends on prokaryotes

For example, the ecological communities of hydrothermal vents depend on chemoautotrophic bacteria for energy

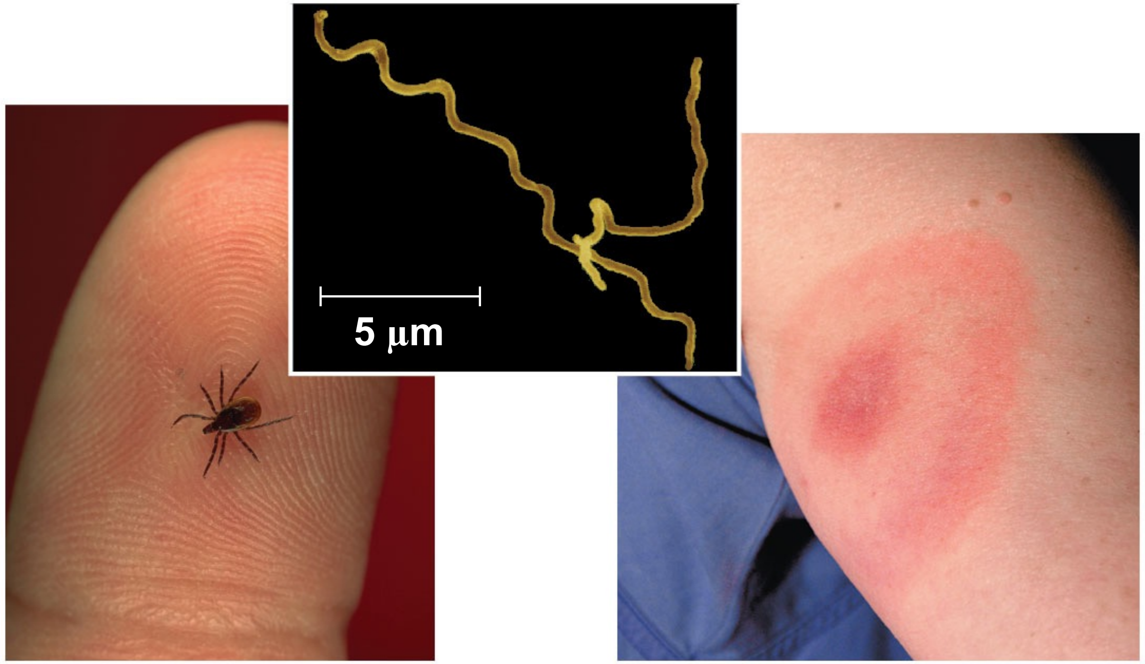

A
Cooperation
B
Competition
Public goods sharing
Cross-feeding
Cheating
C
Predation
Solitary hunting
Group hunting
Interference

Mutualistic Bacteria

- Human intestines are home to about 500–1,000 species of bacteria
- Many of these are mutualists and break down food that is undigested by our intestines

Pathogenic Bacteria

- Bacteria cause about half of all human diseases
- Some bacterial diseases are transmitted by other species
  - For example, Lyme disease is caused by a bacterium and carried by ticks



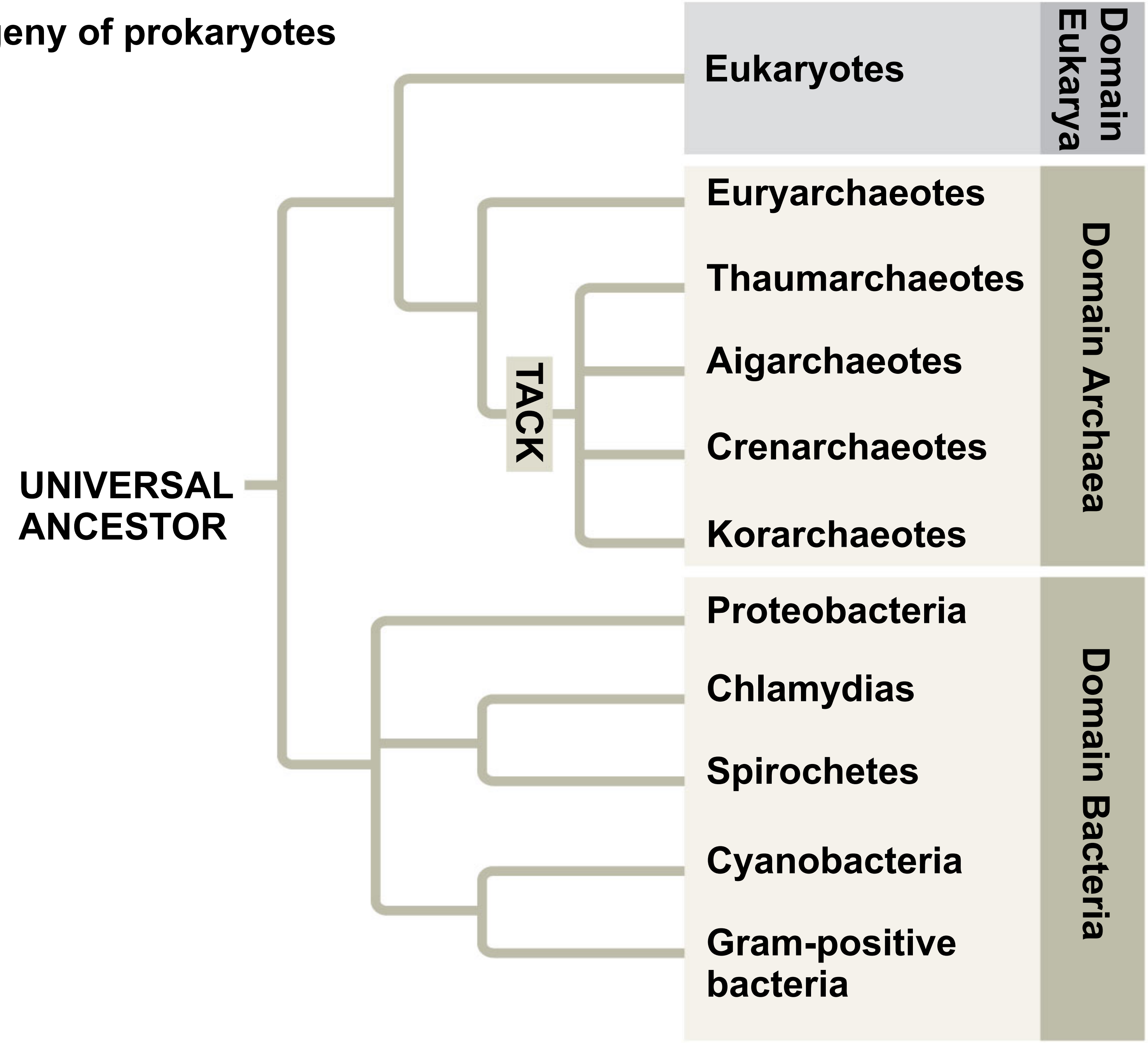
- Pathogenic prokaryotes typically cause disease by releasing exotoxins or endotoxins
- **Exotoxins** are secreted and cause disease even if the prokaryotes that produce them are not present
- **Endotoxins** are released only when bacteria die and their cell walls break down

- Horizontal gene transfer can spread genes associated with virulence
  - For example, pathogenic strains of *E. coli* contain genes that were acquired through transduction

Prokaryotes have radiated into a diverse set of lineages

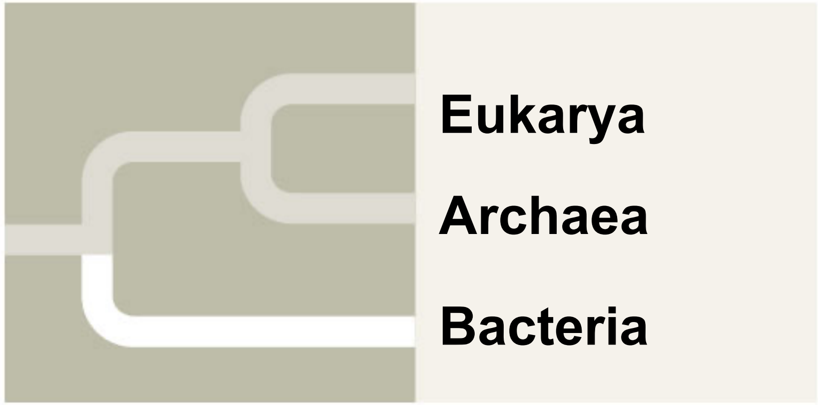
- The origin of prokaryotes dates back to 3.5 billion years ago
- Prokaryotes now inhabit every environment known to support life
- Advances in genomics are beginning to reveal the extent of prokaryotic diversity

A simplified phylogeny of prokaryotes



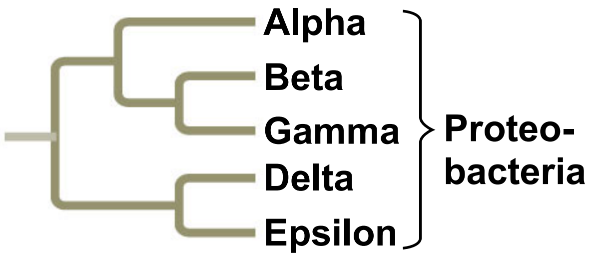
Bacteria

- Bacteria include the vast majority of prokaryotic species familiar to most people
- Diverse nutritional types are represented among bacteria



Proteobacteria

- These gram-negative bacteria include photoautotrophs, chemoautotrophs, and heterotrophs
- Some are anaerobic and others aerobic
- There are currently five subgroups of proteobacteria recognized by molecular systematists



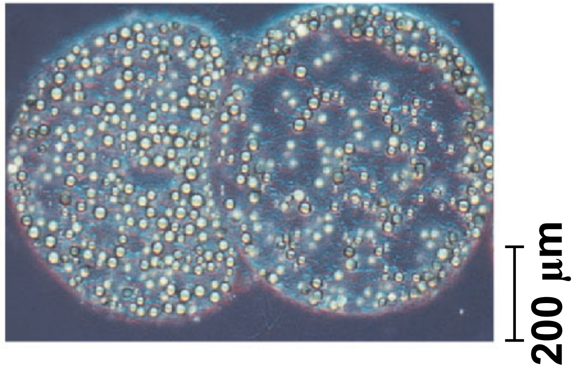
Alpha subgroup

Rhizobium (arrows)
(TEM)

Beta subgroup

Nitrosomonas
(TEM)

Gamma subgroup

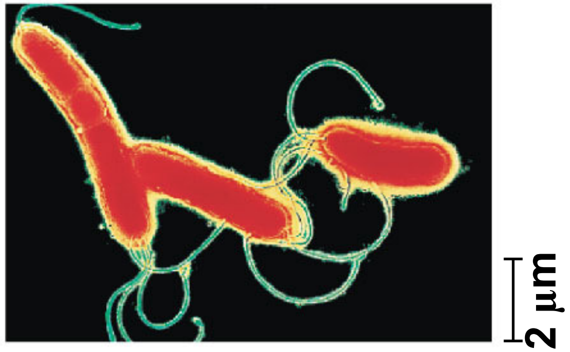


Thiomargarita namibiensis (LM)

Delta subgroup

Chondromyces crocatus (SEM)

Epsilon subgroup



Helicobacter pylori
(TEM)

Subgroup: Alpha Proteobacteria

- Many species are closely associated with eukaryotic hosts
- Scientists hypothesize that mitochondria evolved from aerobic alpha proteobacteria through endosymbiosis

Example: *Rhizobium*, which forms root nodules in legumes and fixes atmospheric N_2
Example: *Agrobacterium*, which produces tumors in plants and is used in genetic engineering

Alpha subgroup

Rhizobium **(arrows) inside a root cell of a legume (TEM)**

Subgroup: Beta Proteobacteria

- This subgroup is nutritionally diverse
- Example: the soil bacterium *Nitrosomonas* converts NH_4^+ to NO_2^-
- Other members include aquatic species and pathogens

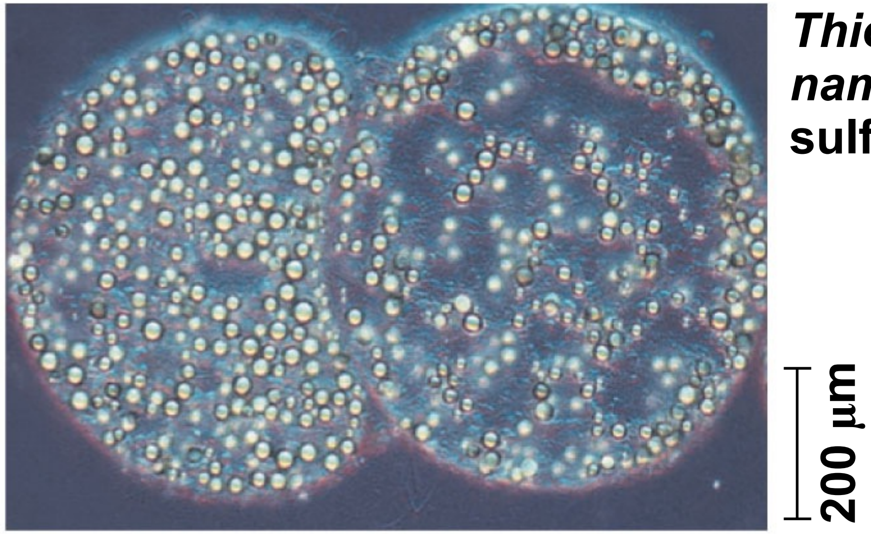
Beta subgroup

Nitrosomonas
(colorized TEM)

Subgroup: Gamma Proteobacteria

- Autotrophic members include sulfur bacteria such as *Thiomargarita namibiensis*
- Some heterotrophs are pathogenic, such as *Legionella*, *Salmonella*, and *Vibrio cholerae*
- *Escherichia coli* resides in the intestines of many mammals and is not normally pathogenic

Gamma subgroup

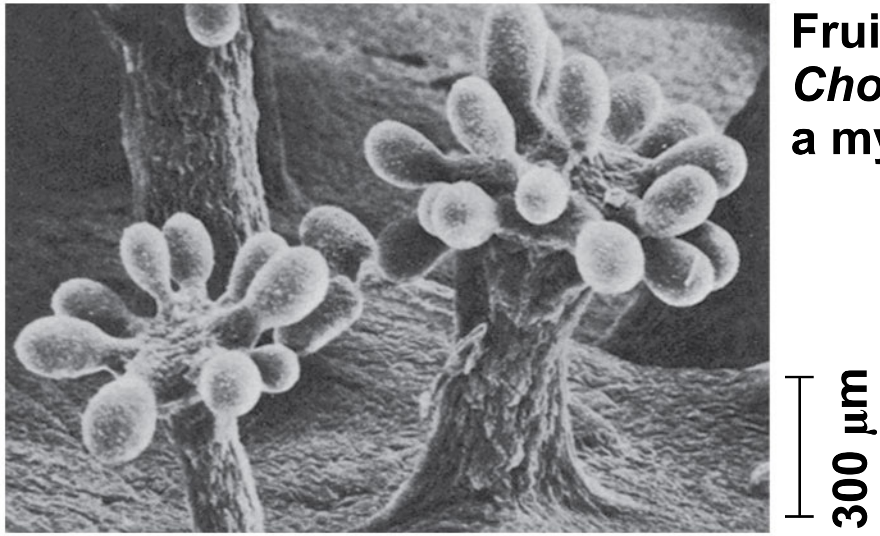


Thiomargarita namibiensis **containing sulfur wastes (LM)**

Subgroup: Delta Proteobacteria

- Example: the slime-secreting myxobacteria, which produces drought-resistant “myxospores”
- Example: bdellovibrios, which mount high-speed attacks on other bacteria

Delta subgroup

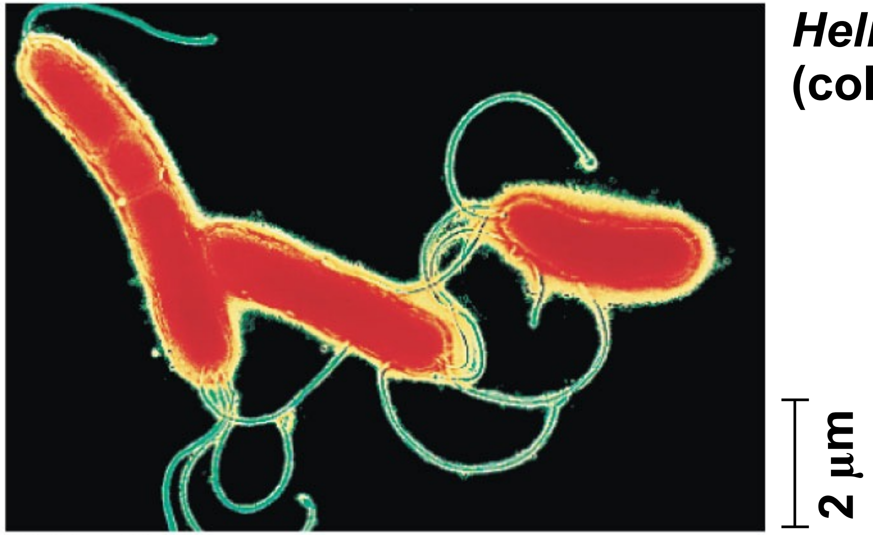


Fruiting bodies of *Chondromyces crocatus*, a myxobacterium (SEM)

Subgroup: Epsilon Proteobacteria

- Most species in this subgroup are pathogenic
- Examples include *Campylobacter*, which causes blood poisoning, and *Helicobacter pylori*, which causes stomach ulcers

Epsilon subgroup

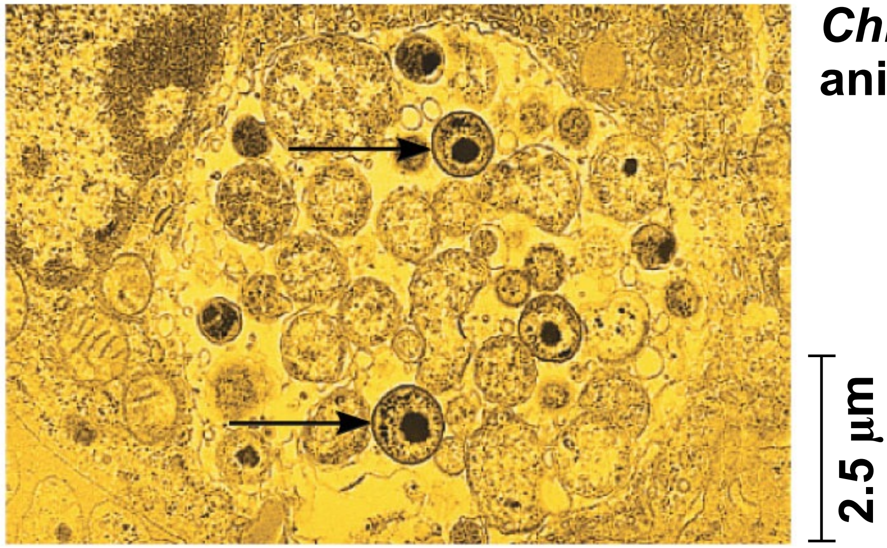


Helicobacter pylori
(colorized TEM)

Chlamydias

- These bacteria are parasites that live within animal cells
- Example: *Chlamydia trachomatis* causes blindness and nongonococcal urethritis by sexual transmission

Chlamydias

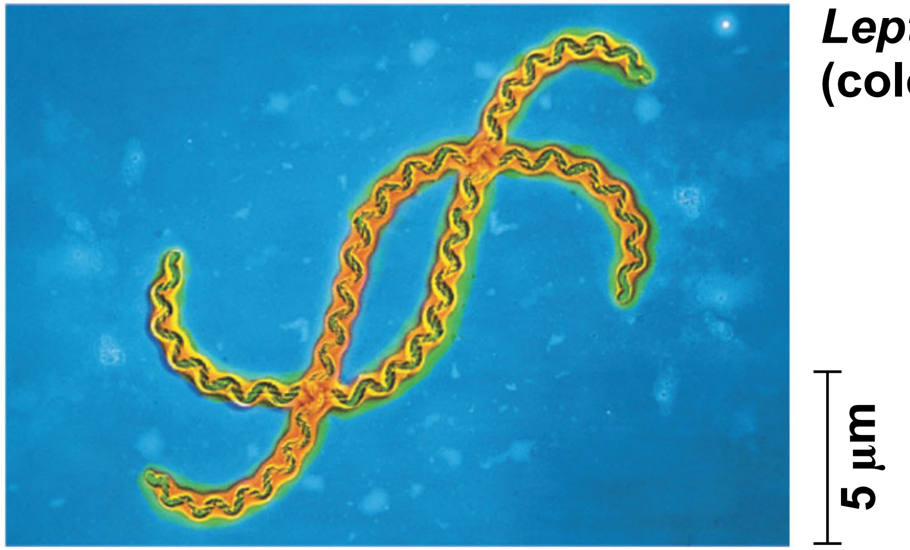


Chlamydia **(arrows) inside an animal cell (colorized TEM)**

Spirochetes

- These bacteria are helical gram-negative heterotrophs
- Some are parasites, including *Treponema pallidum*, which causes syphilis, and *Borrelia burgdorferi*, which causes Lyme disease

Spirochetes

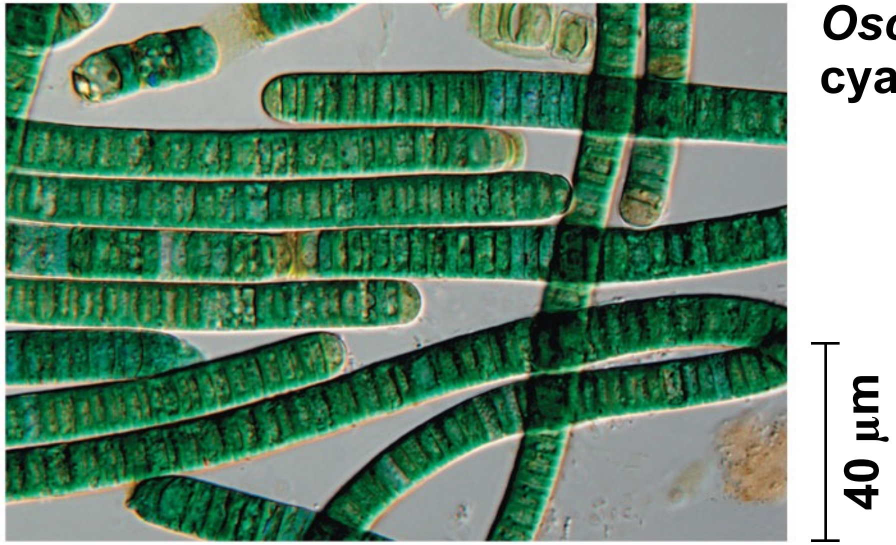


***Leptospira*, a spirochete (colorized TEM)**

Cyanobacteria

- These are gram-negative photoautotrophs that generate O_2
- Plant chloroplasts likely evolved from cyanobacteria by the process of endosymbiosis
- Cyanobacteria are abundant components of freshwater and marine phytoplankton

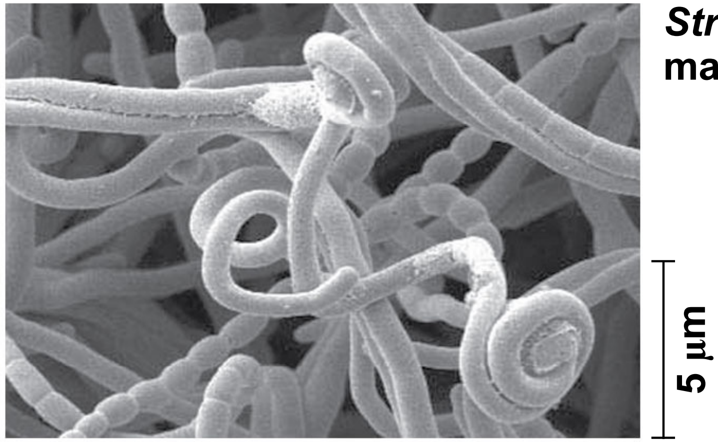
Cyanobacteria



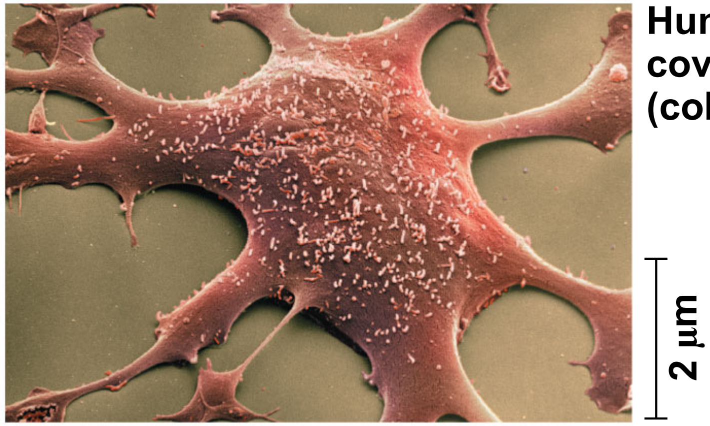
***Oscillatoria*, a filamentous cyanobacterium**

Gram-Positive Bacteria

- Gram-positive bacteria include
  - Colony-forming groups, such as actinomycetes, many of which help decompose organic matter
  - Solitary species including *Bacillus anthracis*, the cause of anthrax; *Clostridium botulinum*, the cause of botulism; and various *Staphylococcus* and *Streptococcus* species
  - Mycoplasmas, the smallest known cells, lack cell walls



***Streptomyces*, the source of many antibiotics (SEM)**



Hundreds of mycoplasmas covering a human fibroblast cell (colorized SEM)

Three domains of life

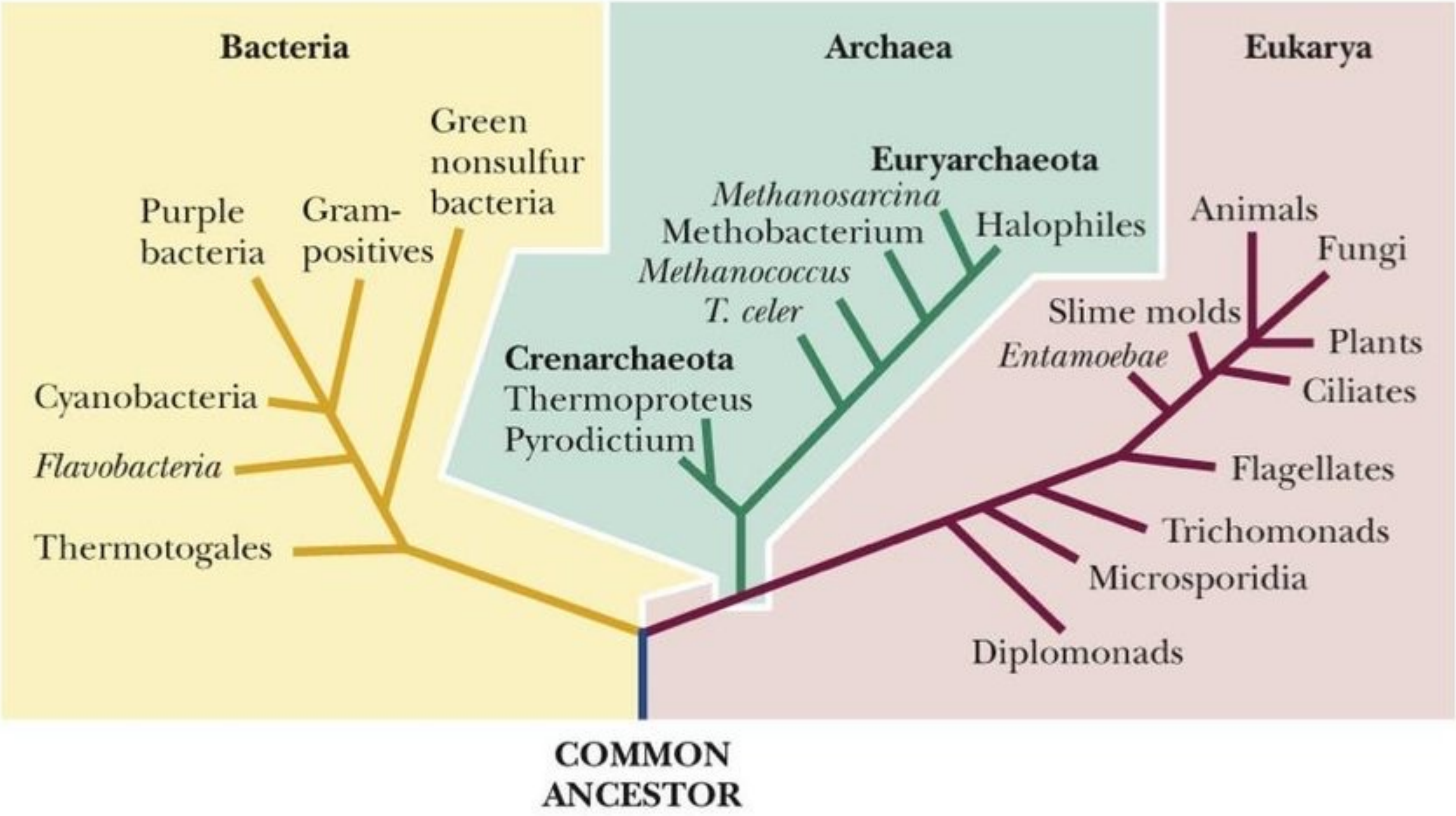
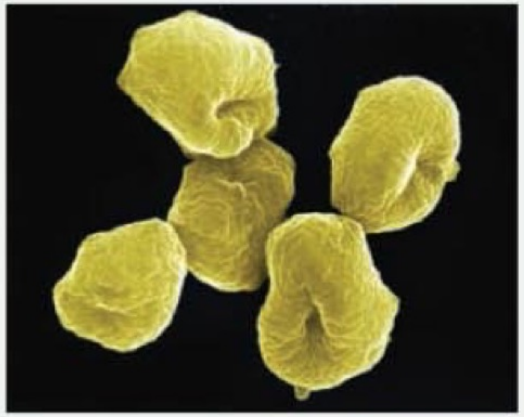
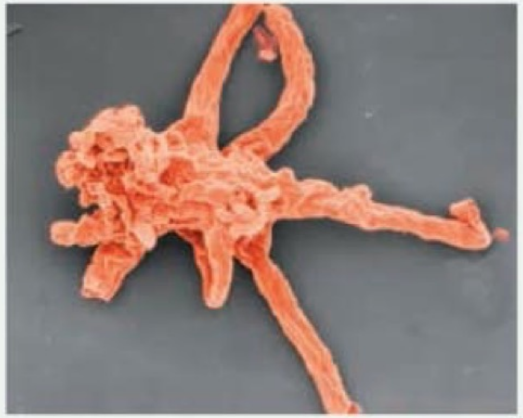
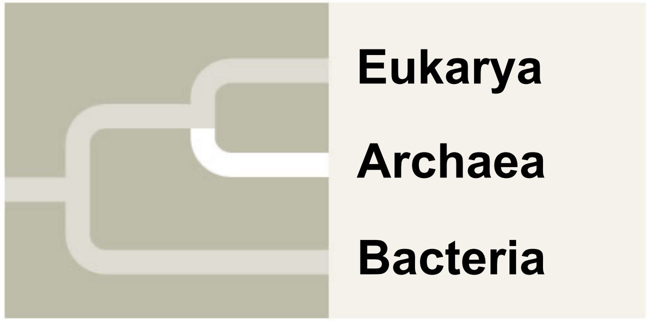


TABLE 10.1 Some Characteristics of Archaea, Bacteria, and Eukarya

	Archaea	Bacteria	Eukarya
			
	Sulfolobus sp. SEM 1 μm	*E. coli* SEM 1 μm	*Amoeba* sp. SEM 5 μm
Cell Type	Prokaryotic	Prokaryotic	Eukaryotic
Cell Wall	Varies in composition; contains no peptidoglycan	Contains peptidoglycan	Varies in composition; contains carbohydrates
Membrane Lipids	Composed of branched carbon chains attached to glycerol by ether linkage	Composed of straight carbon chains attached to glycerol by ester linkage	Composed of straight carbon chains attached to glycerol by ester linkage
First Amino Acid in Protein Synthesis	Methionine	Formylmethionine	Methionine

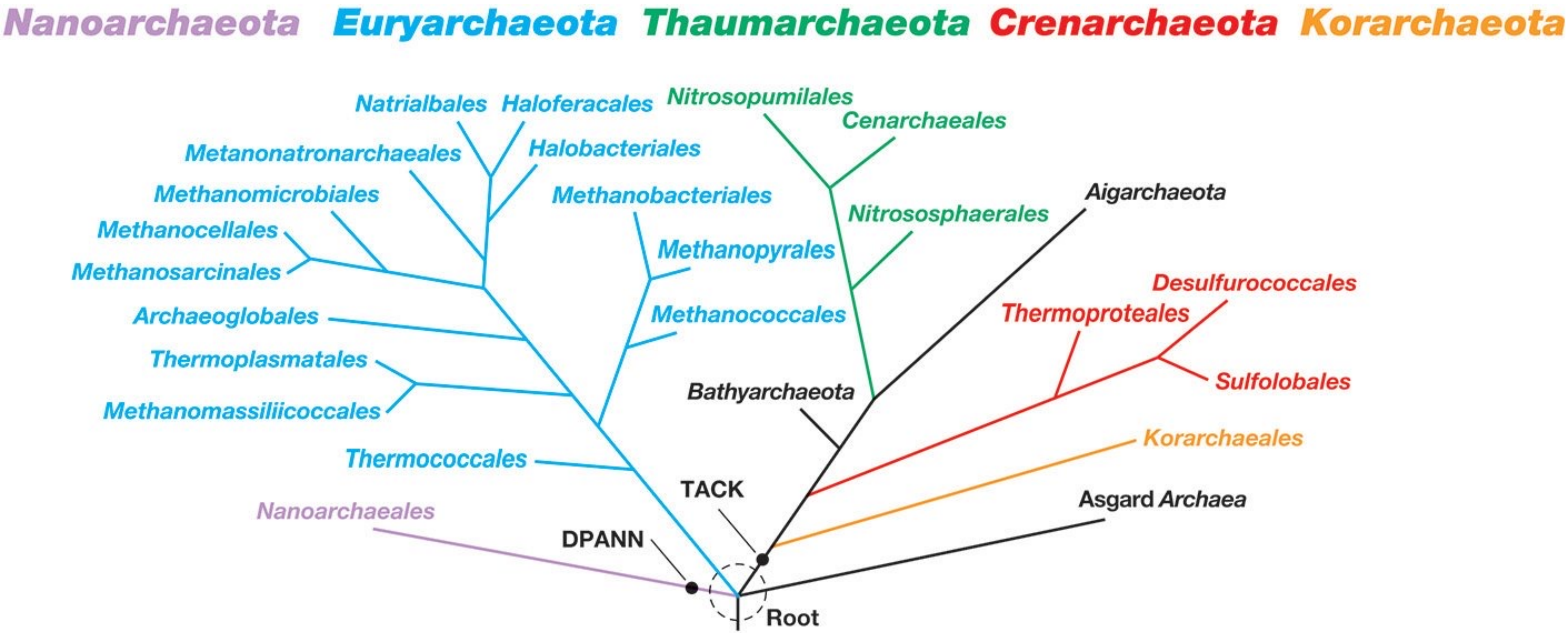
Diversity of *Archaea*

- ***Archaea*** named for Archaean eon, when life first spread across earth
- ***Archaea*** share many characteristics with both Bacteria and ***Eukarya***
  - Archaeal cells likely contributed to the origin of ***Eukarya***
  - Nearly as diverse as ***Bacteria*** but are difficult to culture



Diversity of *Archaea*

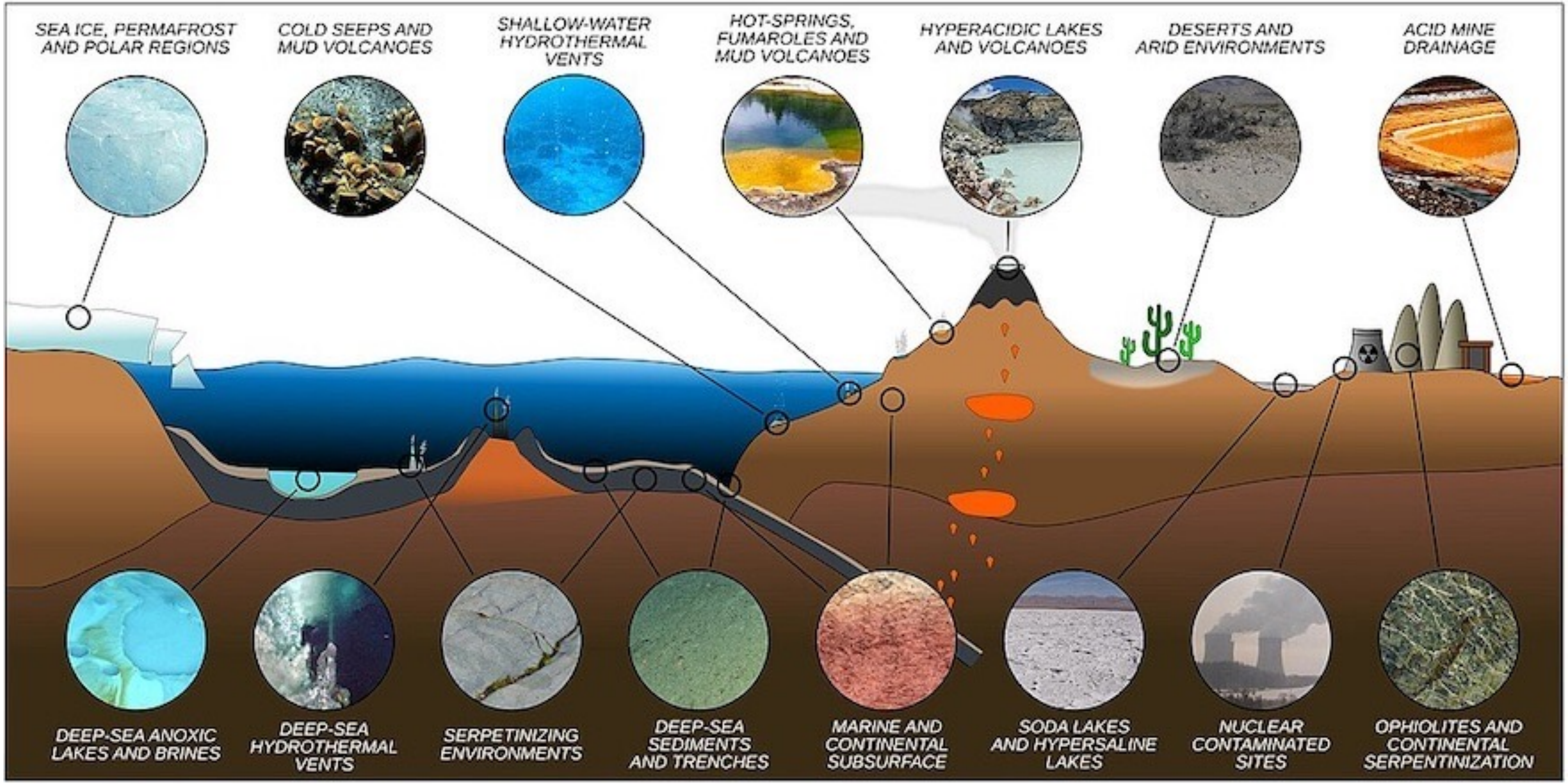
- ***Archaea*** are split into five major groups
  - ***Euryarchaeota*** (better characterized)
  - ***Crenarchaeota*** (better characterized)
  - ***Thaumarchaeota*** (several species isolated)
  - ***Korarchaeota*** (only coculture or enrichment)
  - ***Nanoarchaeota*** (only coculture or enrichment)
- New representative discovered recently through metagenomics and single-cell sequencing



Nanoarchaeota
Euryarchaeota
Thaumarchaeota
Crenarchaeota
Korarchaeota
Natrialbales
Haloferacales
Nitrosopumilales
Cenarchaeales
Metanonatronarchaeales
Halobacteriales
Methanomicrobiales
Methanobacteriales
Aigarchaeota
Nitrososphaerales
Methanocellales
Methanopyrales
Methanosarcinales
Desulfurococcales
Archaeoglobales
Methanococcales
Thermoproteales
Thermoplasmatales
Sulfolobales
Methanomassiliicoccales
Bathyarchaeota
Korarchaeales
Thermococcales
TACK
Asgard Archaea
Nanoarchaeales
DPANN
Root

Diversity of *Archaea*

- Common traits
  - Ether-linked lipids
  - Lack of peptidoglycan in cell walls
  - Structurally complex RNA polymerases similar to those of ***Eukarya***
- Contemporary species are metabolically diverse
  - Chemoorganotrophs or chemolithotrophs; respiratory or fermentative; aerobic or anaerobic
- Some traits only found in ***Archaea***
  - Only domain that makes methane (***methanogens*****;** ***Euryarchaeota***)
  - Many ***Archaea*** live in extreme environments (extremophiles: hyperthermophiles, halophiles, acidophiles, psychrophiles)



SEA ICE, PERMAFROST AND POLAR REGIONS
COLD SEEPS AND MUD VOLCANOES
SHALLOW-WATER HYDROTHERMAL VENTS
HOT-SPRINGS, FUMAROLES AND MUD VOLCANOES
HYPERACIDIC LAKES AND VOLCANOES
DESERTS AND ARID ENVIRONMENTS
ACID MINE DRAINAGE
DEEP-SEA ANOXIC LAKES AND BRINES
DEEP-SEA HYDROTHERMAL VENTS
SERPETINIZING ENVIRONMENTS
DEEP-SEA SEDIMENTS AND TRENCHES
MARINE AND CONTINENTAL SUBSURFACE
SODA LAKES AND HYPERSALINE LAKES
NUCLEAR CONTAMINATED SITES
OPHIOLITES AND CONTINENTAL SERPENTINIZATION

Table 27.2 A Comparison of the Three Domains of Life

CHARACTERISTIC	DOMAIN		
	Bacteria	Archaea	Eukarya
Nuclear envelope	Absent	Absent	Present
Membrane-enclosed organelles	Absent	Absent	Present
Peptidoglycan in cell wall	Present	Absent	Absent
Membrane lipids	Unbranched hydro-carbons	Some branched hydrocarbons	Unbranched hydro-carbons
RNA polymerase	One kind	Several kinds	Several kinds
Initiator amino acid for protein synthesis	Formyl-methionine	Methionine	Methionine

Table 27.2 A Comparison of the Three Domains of Life

CHARACTERISTIC	DOMAIN		
	Bacteria	Archaea	Eukarya
Introns in genes	Very rare	Present in some genes	Present in many genes
Response to the antibiotics streptomycin and chloramphenicol	Growth usually inhibited	Growth not inhibited	Growth not inhibited
Histones associated with DNA	Absent	Present in some species	Present
Circular chromosome	Present	Present	Absent
Growth at temperatures $> 100°C$	No	Some species	No

Prokaryotes play crucial roles in the biosphere

- Prokaryotes are so important that if they were to disappear, the prospects for any other life surviving on Earth would be dim

Chemical Recycling

- Prokaryotes play a major role in the recycling of chemical elements between the living and nonliving components of the environment
- Some chemoheterotrophic prokaryotes function as **decomposers**, breaking down dead organisms and waste products

- Prokaryotes can convert some molecules to forms that can be taken up by other organisms
  - For example, under some conditions, prokaryotes can increase the availability of nutrients required for plant growth
- Prokaryotes can also “immobilize” or decrease the availability of nutrients by using them in their own cells