Learning unit 2: Prokaryotes and the origins of metabolic diversity

2.1 Introduction

To complete the learning unit, you will need to refer to pages 629–648 chapter 27 in Campbell et al. (2015)

Organisms informally called prokaryotes, have inhabited planet earth for more than 3.5 billion years. Indeed, their existence can be pronounced much longer than eukaryotes, which evolved at least 2.2 billion years ago. Although prokaryotes are microscopic, they are so numerous that they probably account for more than half of earth's biomass. Prokaryotic species are well known to adapt to a vast range in the land and water. Prokaryotes can tolerate extreme conditions, such as very low pH, too cold and/or too hot, and some have even been found living within rocks 3.2 km below earth's surface. Their ability to adapt to a broad range of habitats helps scientists to explain why prokaryotes are the most abundant organisms on earth.

Members of domain bacteria and archaea cause many diseases, such as tuberculosis, tetanus, respiratory infections, and food poisoning in humans. However, both bacteria and archaea play very essential role in the biosphere. As decomposers they break down organic molecules into their components. Without these remarkable microorganisms, certain elements such as carbon, nitrogen, and phosphorus, would remain locked up in the wastes and dead bodies of plants and animals.

In this learning unit, we will describe the structure of bacteria and archaea. We will also examine the adaptations, diversity, and enormous ecological impact of these remarkable organisms.

2.2 Learning outcomes

By the end of this learning unit you should be able to

• name the two main branches of prokaryotic evolution

• describe the structure, function and reproduction of bacteria

• discuss the ecological impact of bacteria

• describe the organisation and specialisation of a bacterial cell

• describe the structure, composition and function of prokaryotic cell walls

• distinguish between the staining properties of gram-positive and gram-negative bacteria

• explain how the genetic organisation of the prokaryotic genome differs from that of eukaryotic cells

2.3 Structure, function and reproduction of bacteria

Recommended reading: pages 630–636 chapter 27 in Campbell et al. (2015)

Prokaryotes seem to be found everywhere. Collective prokaryote biomass outweighs all eukaryotes combined by at least tenfold. They exist almost everywhere, including places where eukaryotes cannot. Most prokaryotes are beneficial; human could not live without them, for example, nitrogen-fixing bacteria. There are approximately 5 000 species of prokaryotes that have been identified, however, estimation of prokaryote diversity range from 400,000 to 4,000,000 species. Bacteria and archaea are the two main branches of prokaryote evolution. Archaea are thought to be more closely related to eukaryotes than to bacteria. Most prokaryotes are unicellular. Although, they are unicellular and small, prokaryotes are well organised, achieving all of an organism's life functions within a single cell (Figure 2.1). Some species form aggregates of two or more individuals. Prokaryotes are typically 0.5-5 μm in diameter, but some can be seen by the naked eye. Eukaryotic cells are typically 10-100 μm in diameter. Almost all prokaryotes have cell walls external to the plasma membrane.

Figure 2.1: Prokaryotic cell.

(https://commons.wikimedia.org/wiki/File:Average_prokaryote_cell-_en.svg)

A key feature of nearly all prokaryotic cells is the cell wall, which maintains cell shape, protects the cell, and prevents it from bursting in a hypotonic environment. There are three (3) common shapes: cocci (round); bacilli (rod); helical (spiral). Refer to your textbook, page 630, figure 27.2. Cell walls are composed of peptidoglycan. There are two types of cell walls. Bacteria are grouped according to cell wall type, and that is Gram-positive bacteria and Gram-negative bacteria. Gram-positive bacteria have simple, thick cell walls. Their cell walls are composed of a relatively large amount of peptidoglycan. Whereas, Gram-negative bacteria have less peptidoglycan and are more complex. They have a peptidoglycan layer surrounded by the plasma membrane and an outer membrane. Gram-negative bacteria are typically more resistant to host immune defense and antibiotics. Note that the two types of bacteria can be stained to determine which is gram-negative (pink) and gram-positive (purple) using a Gram Stain.

Most prokaryotes secrete sticky substances that form a protective layer and enable them to adhere to substrates. The sticky protective layer secreted by prokaryotes is called the **capsule**. Endospores are resistant cells formed by certain bacteria as a way to withstand harsh conditions. The cell replicates its chromosome and wraps it in a durable wall that can protect the chromosome from adverse conditions, e.g. boiling water, desiccation. When the environment is good again, the cell will revive to a new vegetative (growing) spore.

Some prokaryotes adhere to substrates using pili. Some pili are specialized for DNA transfer. This process is called **conjugation**.

Many prokaryotes are motile. Moreover, some exceed speeds 100 times their body length per second. The mode of movement is executed by three types, namely; flagellum - basal apparatus rotates the flagellum and propels the cell, corkscrew movement of spirochetes (helical), and finally, some prokaryotes glide over jets of slimy secretions.

Many prokaryotes move toward or away from stimulus-taxis. Chemotaxis is the movement toward or away from a chemical.

Neither mitosis nor meiosis occur in the prokaryotes. Reproduction is asexual by *binary fission*. DNA synthesis is almost continuous. Prokaryotes grow and adapt rapidly. The doubling time for *E. coli* is 20 minutes. Start with one *E. coli* cell. After 48 hours of doubling every 20 minutes, the mass of *E. coli* would be 10,000 times the mass of the earth. Bacteria do not have gene transfer by sexual reproduction, but do transfer genes. Why? This is an aid in adapting (evolving). Three (3) ways for genes to be transferred between cells:

Transformation – cell takes up genes from the surrounding environment.

Conjugation – direct transfer of genes from one prokaryote to another. Use the sex pilus to conjugate.

Transduction – viruses transfer genes between prokaryotes.

2.3.1 Activity 2.1

Do this activity and add it to your portfolio.

Refer to your textbook and answer the following questions :

b. Describe the differences between eukaryotic cells and prokaryotic cells.
d. Discuss the structure of the prokaryotic cell wall and explain how the structure could be of medical value.
f. What is a gram stain and why is it of importance to doctors?

2.3.2 Feedback on activity 2.1

You may answer a) in the form of table as shown below:

	Eukaryotic cell	**Prokaryotic cell**
Nucleus	Present	Absent
Number of chromosomes	More than one	One, but not true chromosome
Cell type	Usually multicellular	Usually unicellular
Mitochondria	Present	Absent
Chloroplasts	Present (in plants)	Absent
Cell size	Large (10- 100 um)	Small (1- 10 um)
Structural complexity	complex	Much simpler
DNA found in the region	Nucleus	Nucleoid
Membrane-enclosed organelles	Present	Absent
Lysosomes and peroxisomes	Present	Absent
Endoplasmic reticulum	Present	Absent
Golgi apparatus	Present	Absent

Permeability of nuclear membrane	Selective	Not present
Plasma membrane	Present	Present
Cytosol	Present	Present
Cell division	Mitosis	Binary fission
Ribosomes	Present (larger)	Present (smaller)

In answering b) A cell wall is a layer located outside the cell membrane found in plants, fungi, bacteria, algae, and archaea. A peptidoglycan cell wall composed of disaccharides and amino acids gives bacteria structural support. The bacterial cell wall is often a target for antibiotic treatment.

In answering c) Gram stain is a method of staining bacteria using a dye called crystal violet. Gram stain is important in that, it helps distinguish between different types of bacteria.

2.4 Nutritional and metabolic adaptations

Recommended reading: pages 637- 638 of chapter 27 in Campbell et al. (2015)

All prokaryotes (as well as eukaryotic species) are grouped into four (4) categories according to how they obtain energy and carbon. Refer to your textbook, table 27.1, page 638. Species that use light energy are *phototrophs*.

Species that obtain energy from chemicals in their environment are chemotrophs. Organisms that need only CO_2 as a carbon source are autotrophs. Organisms that require at least one organic nutrient as a carbon source are heterotrophs. These categories of energy source and carbon source can be combined to group prokaryotes according to four major modes of nutrition.

Mode	**Energy source**	**Carbon source**	**Types of organisms**
Autotroph			
Photoautotrophs	Since they are photosynthetic species, they use light as the energy source	CO_2, HCO_3^-, or related compound is the carbon source	Cyanobacteria; plants (eukaryotic)
Chemoautotrophs	Energy from oxidation of inorganic substances (e.g. NH_4, and S)	CO_2 is the carbon source	*Sulfolobus, Beggiatoa*
Heterotroph			
Photoheterotrophs	Light as energy source	Organic compounds are source of carbon	Unique to certain aquatic and salt loving prokaryotes (e.g. *Rhodobacter*, *Chloroflexus*)
Chemoheterotrophs	Organic compounds are energy source	Organic compounds are source of carbon (this includes humans)	Many prokaryotes (*Clostridium)*; animals and fungi (eukaryotic); some plants

The role of Oxygen in metabolism

Prokaryotic metabolism also varies with respect to oxygen (O_2). The following are the three different groups:

(i) Obligate aerobes - Use O_2 for respiration; cannot grow without it. (Humans are obligate aerobes)

(ii) Facultative aerobes - Use O_2 when available; ferment when O_2 isn't available.

(iii) Obligate anaerobes - Poisoned by O_2; use fermentation or live by anaerobic respiration. In anaerobic respiration, inorganic molecules like SO_4^{2-}, NO_3, and Fe_3^+ are used instead of oxygen.

It should be noted that photosynthesis evolved early in prokaryotic life. Since, Cyanobacteria started to produce O_2 about 2.7 billion years ago. Contrasting hypotheses for the taxonomic distribution of photosynthesis among prokaryotes.

2.4.1 Activity 2.2

Do this activity and add it to your portfolio.

Refer to your textbook and answer the following questions:

b. Describe the differences between photoautotrophs and photoheterotrophs.
d. List and describe the three groups of prokaryotes with respect to oxygen.

2.4.2 Feedback on activity 2.2

In answering question a), Photoautotrophs convert inorganic materials into organic materials for use in cellular functions such as biosynthesis and respiration and provide nutrition for many other forms of life. Photoheterotrophs depend on light for their source of energy and mostly organic compounds from the environment for their source of carbon.

b) You should be able to name Obligate aerobes, Facultative aerobes and Obligate anaerobes. You should also describe the manner in which they differ from one another

2.5 Prokaryotes have radiated into diverse set of lineages

Recommended reading: pages 639–643 of chapter 27 in Campbell et al. (2015)

Since their origin 3.5 billion years ago, prokaryotic populations have radiated extensively as a wide range of structural and metabolic adaptations have evolved in them. Collectively, these adaptations have enabled prokaryotes to inhabit every environment known to support life. In recent decades, advances in genomics are beginning to reveal the extent of prokaryotic diversity.

Early on prokaryotes diverged into two lineages, the domains archaea and bacteria. A comparison of the three domains -- Archaea, Bacteria, and Eukarya -- demonstrates that Archaea have at least as much in common with eukaryotes as with bacteria (refer to your textbook page 642, table 27.2). The archaea also have many unique characteristics. Most species of archaea have been sorted into the kingdom Euryarchaeota or the kingdom Crenarchaeota. However, much of the research on archaea has focused not on phylogeny, but on their ecology - their ability to live where no other life can. Archaea are **extremophiles**, "lovers" of extreme environments. Based on environmental criteria, archaea can be classified into **methanogens**, **extreme halophiles**, and **extreme thermophiles**. Methanogens obtain energy by using CO_2 to oxidize H_2 replacing methane as a waste. Methanogens are among the strictest anaerobes.

They live in swamps and marshes where other microbes have consumed all the oxygen. Methanogens are important decomposers in sewage treatment. Other methanogens live in the anaerobic guts of herbivorous animals, playing an important role in their nutrition. They may contribute to the greenhouse effect, through the production of methane.

Extreme halophiles live in such saline places as the Great Salt Lake and the Dead Sea. Some species merely tolerate elevated salinity; others require an extremely salty environment to grow.

Colonies of halophiles form a purple-red scum from bacteriorhodopsin, a photosynthetic pigment very similar to the visual pigment in the human retina. Extreme thermophiles thrive in hot environments. The optimum temperatures for most thermophiles are 60°C-80°C. Sulfolobus oxidizes sulphur in hot sulphur springs in Yellowstone National Park. Another sulphur-metabolizing thermophile lives at 105°C water near deep-sea hydrothermal vents.

If the earliest prokaryotes evolved in extremely hot environments like deep-sea vents, then it would be more accurate to consider most life as "cold-adapted" rather than viewing thermophilic archaea as "extreme". Recently, scientists have discovered an abundance of marine archaea among other life forms in more moderate habitats.

2.5.1 Activity 2.3

Do this activity and add it to your portfolio.

Refer to your textbook and answer the following questions:

a) Describe the difference between extreme halophiles and extreme thermophiles.

b) In your understanding, what makes the archaea "lovers" of extreme environments?

2.5.2 Feedback on activity 2.3

In answering question a), did you note that the major difference is that halophiles live in environments with plenty of salt concentration and thermophiles live in geothermal areas where there is plenty of heat.

b) Do not forget to consider their physiological aspects and their extreme tolerance.

2.6 Prokaryotes play crucial roles in the biosphere

Recommended reading: pages 643–646 of chapter 27 in Campbell et al. (2015)

If people were to disappear from the planet tomorrow, life on earth would change for many species, but few would be driven to extinction. In contrast, prokaryotes are so important to the biosphere that if they were to disappear, the prospects of survival for many other species would be dim.

2.6.1 Chemical recycling

Ongoing life depends on the recycling of chemical elements between the biological and chemical components of ecosystems. If it were not for decomposers, especially prokaryotes, carbon, nitrogen, and other elements essential for life would become locked in the organic molecules of corpses and waste products. Prokaryotes also mediate the return of elements from the non-living components of the environment to the pool of organic compounds.

Prokaryotes have many unique metabolic capabilities. They are the only organisms able to metabolize inorganic molecules containing elements such as iron, sulphur, nitrogen, and hydrogen. Cyanobacteria not only synthesise food and restore oxygen to the atmosphere, but they also fix nitrogen. This stocks the soil and water with nitrogenous compounds that other organisms can use to make proteins. When plants and animals die, other prokaryotes return the nitrogen to the atmosphere.

2.6.2 Ecological interactions

Prokaryotes often interact with other species of prokaryotes or eukaryotes with complementary metabolisms. Organisms involved in an ecological relationship with direct contact (**symbiosis**) are known as **symbionts**. If one symbiont is larger than the other, it is also termed the host.

In **commensalism**, one symbiont receives benefits while the other is not harmed or helped by the relationship. In **parasitism**, one symbiont, the parasite, benefits at the expense of the host. In **mutualism**, both symbionts benefit.

For example, while the fish provides bioluminescent bacteria under its eye with organic materials, the fish uses its living flashlight to lure prey and to signal potential mates. Prokaryotes are involved in all three categories of symbiosis with eukaryotes. Legumes (peas, beans, alfalfa, and others) have lumps in their roots which are the homes of mutualistic prokaryotes (Rhizobium) that fix nitrogen that is used by the host. The plant provides sugars and other organic nutrients to the prokaryote.

Fermenting bacteria in the human vagina produce acids that maintain a pH between 4.0 and 4.5, suppressing the growth of yeast and other potentially harmful microorganisms. However, other bacteria are pathogens.

2.6.3 Pathogenic bacteria

Exposure to pathogenic prokaryotes is a certainty. Most of the time our defenses check the growth of these pathogens. Occasionally, the parasite invades the host, resists internal defense long enough to begin growing, and then harms the host. Pathogenic prokaryotes cause about half of all human disease, including pneumonia caused by *Haemophilus influenzae* bacteria. Some pathogens are opportunistic. These are normal residents of the host, but only cause illness when the host's defenses are weakened.

Louis Pasteur, Joseph Lister, and other scientists began linking disease to pathogenic microbes in the late 1800s. Robert Koch was the first to connect certain diseases to specific bacteria. He identified the bacteria responsible for anthrax and the bacteria that cause tuberculosis. Koch's methods established four criteria, Koch's postulates, that still guide medical microbiology.

(i) The researcher must find the same pathogen in each diseased individual investigated,

(ii) Isolate the pathogen form the diseased subject and grow the microbe in pure culture,

(iii) Induce the disease in experimental animals by transferring the pathogen from culture, and

(iv) Isolate the same pathogen from experimental animals after the disease develops.

These postulates work for most pathogens, but exceptions do occur. Some pathogens produce symptoms of disease by invading the tissues of the host. The actinomycete that causes tuberculosis is an example of this source of symptoms. More commonly, pathogens cause illness by producing poisons, called **exotoxins** and **endotoxins**. Exotoxins are proteins secreted by prokaryotes. **Exotoxins** can produce disease symptoms even if the prokaryote is not present. *Clostridium botulinum*, which grows anaerobically in improperly canned foods, produces an exotoxin that causes botulism.

An exotoxin produced by *Vibrio cholerae* causes cholera, a serious disease characterized by severe diarrhea. Even strains of *E. coli* can be a source of exotoxins, causing traveler's diarrhea.

Endotoxins are components of the outer membranes of some gram-negative bacteria. The endotoxin-producing bacteria in the genus *Salmonella* are not normally present in healthy animals. *Salmonella typhi* causes typhoid fever. Other *Salmonella* species, including some that are common in poultry, cause food poisoning. Since the discovery that "germs" cause disease, improved sanitation and improved treatments have reduced mortality and extended life expectancy in developed countries. More than half of our antibiotics (such as streptomycin and tetracycline) come from the soil bacteria *Streptomyces*. The decline (but not removal) of bacteria as threats to health may be due more to public-health policies and education than to "wonder-drugs." For example, Lyme disease, caused by a spirochete spread by ticks that live on deer, field mice, and occasionally humans, can be cured if antibiotics are administered within a month after exposure.

If untreated, Lyme disease causes arthritis, heart disease, and nervous disorders. The best defense is avoiding tick bites and seeking treatment if bitten and a characteristic rash develops. Today, the rapid evolution of antibiotic-resistant strains of pathogenic bacteria is a serious health threat aggravated by imprudent and excessive antibiotic use. Although declared illegal by the United Nations, the selective culturing and stockpiling of deadly bacterial disease agents for use as biological weapons remains a threat to world peace.

2.6.4 Prokaryotes in research and technology

Humans have learned to exploit the diverse metabolic capabilities of prokaryotes for scientific research and for practical purposes. Much of what we know about metabolism and molecular biology has been learned using prokaryotes, especially *E. coli*, as simple model systems. Increasing, prokaryotes are used to solve environmental problems.

The application of organisms to remove pollutants from air, water, and soil is bioremediation. The most familiar example is the use of prokaryote decomposers to treat human sewage. Anaerobic bacteria decompose the organic matter into sludge (solid matter in sewage), while aerobic microbes do the same to liquid wastes. Soil bacteria, called pseudomonads, have been developed to decompose petroleum products at the site of oil spills or to decompose pesticides.

Humans also use bacteria as metabolic "factories" for commercial products. The chemical industry produces acetone, butanol, and other products from bacteria. The pharmaceutical industry cultures bacteria to produce vitamins and antibiotics. The food industry uses bacteria to convert milk to yogurt and various kinds of cheese. The development of DNA technology has allowed genetic engineers to modify prokaryotes to achieve specific research and commercial outcomes.

2.6.5 Activity 2.4

Do this activity and add it to your portfolio.

Refer to your textbook and answer the following questions:

b. Explain why all life on earth depends upon the metabolic diversity of prokaryotes.
d. Distinguish among mutualism, commensalism and parasitism. Describe examples of prokaryotes in each of these relationships.
c. List Koch's postulates that are used to substantiate a specific pathogen as the cause of a disease.
e. Describe the role of prokaryotes in recycling within ecosystems.

2.6.6 Feedback on activity 2.4

a) They possess strange metabolic diversity —*E. coli*, for example, is found in the intestines and excretion of animals BUT if found in drinking water or post-plant sewage, the sewage system is bad. Earth's metabolic diversity is greater among the prokaryotes than all of the eukaryotes.

b) Mutualism

i. Close association in which both benefit

ii. Intestinal flora completes digestion, makes vitamins

iii. Nitrogen fixing bacteria live in legume root nodules

Commensalism

i. One benefits, the other is neutral

ii. Most bacteria on and in humans are commensals

Parasitism

i. One benefits, one is harmed

ii. Bacterial diseases like tuberculosis, leprosy, and anthrax

c) -Find the suspected pathogen in each individual with the disease

-Isolate it from a diseased individual and grow it in the laboratory

-Cause the disease by infecting from the culture

-Re-isolate the pathogen from the experimental infection

d) Prokaryotic decomposers release essential nutrients from dead organisms. Others convert essential nutrients into usable forms. Others replenish the "starting" forms.

2.7 Summary

Prokaryotes (*bacteria*) appeared about 3.5 billion years ago, and were the earliest living organisms and the only forms of life for 2 billion years. Prokaryotes dominate the biosphere; they are the most numerous organisms and can be found in all habitats. Many prokaryotic species can reproduce quickly by binary fission, leading to the formation of populations containing enormous numbers of individuals. Some form endospores, which can remain viable in harsh conditions for centuries.

Because prokaryotes can often proliferate rapidly, mutations can quickly increase a population's genetic variation. As a result, prokaryotic populations often can evolve in short periods of time in response to changing conditions.

Nutritional diversity is much greater in prokaryotes than in eukaryotes. In generally, prokaryotes perform all four modes of nutrition, namely; photoautotrophy, chemoautotrophy, photoheterotrophy, and lastly, chemoheterotrophy. Within prokaryotic species, obligate aerobes require O_2, obligate anaerobes are poisoned by O_2, and facultative anaerobes can survive with or without O_2. Unlike eukaryotes, prokaryotes can metabolise nitrogen in many different forms. Some can convert atmospheric nitrogen to ammonia, a process called nitrogen fixation.

Decomposition by heterotrophic prokaryotes and the synthetic activities of autotrophic and nitrogen-fixation prokaryotes contribute to the recycling of elements in ecosystems. Many prokaryotes have a symbiotic relationship with a host. It is important to note that, the relationships between prokaryotes and their hosts range from mutualism, commensalism to parasitism.

Human depend on mutualistic prokaryotes, including hundreds of species that live in our intestines and help to digest food. Whereas, pathogenic bacteria typically cause disease by either releasing exotoxins or endotoxins.