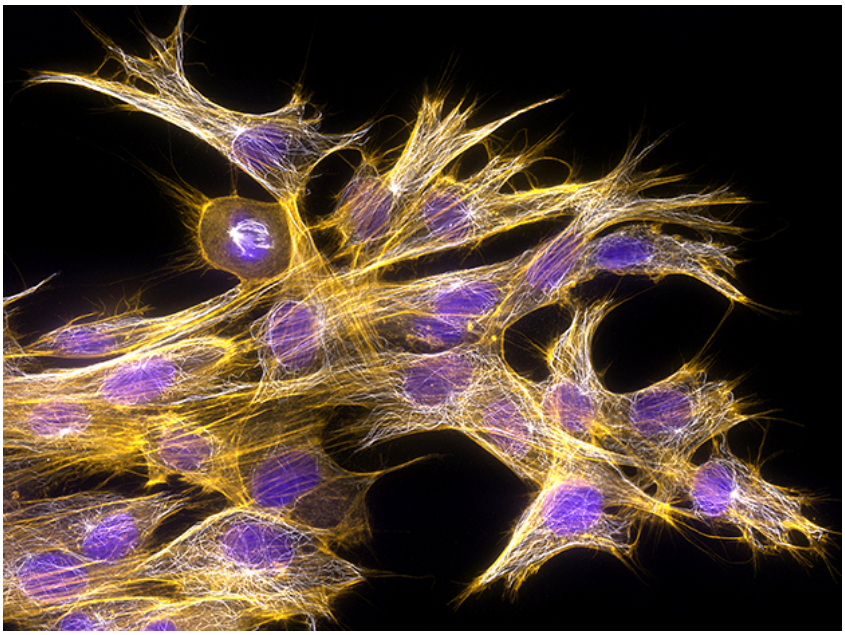
13 Cells

Cells are the basic unit of life.



Fibroblasts are common animal cells responsible for synthesizing extracellular matrix material.
Biologists extensively study these cells because fibroblasts are hearty and grow well in cell culture. These cells, photographed through a fluorescent microscope, have been stained with fluorescent dyes to specifically illuminate the nucleus (purple) and parts of the cytoskeleton (yellow and white).
Dr. Torsten Wittmann/Science Source.

Topics Covered in this Module

- Cells Compose Organisms or Can Be Organisms
- Cell Theory
- Cell Types

Major Objectives of this Module

- Describe key elements of cell theory.
- Explain why cells are limited in size.
- Compare and contrast light and electron microscopes.
- Compare and contrast eukaryotic and prokaryotic cells.
- Identify and discuss functions of prokaryotic cellular structures.

Cells Compose Organisms or Can Be Organisms

What is a human being? The human body contains trillions of cells of which there are hundreds of different types. Each type of cell has a different role in the body's functioning and maintenance of health. For example, nerve cells send and receive messages, muscle cells enable the body to move, and red blood cells carry oxygen. Even though the body is made up of trillions of "human" cells, it contains 10 times more bacterial and archaean cells. Nearly all of these cells (both human and prokaryotic) work together to keep a person alive and healthy. A wide variety of cell types cooperate to produce a multicellular organism. Many other organisms are single-celled and yet are able to carry out all life processes. Although individual cells may have different roles and functions in an organism or ecosystem, cells share the same basic structure and perform many of the same cellular processes.

WHY DOES THIS TOPIC MATTER?

Stem Cells
Stem cells are powerful tools in biology and medicine. What can scientists do with these cells and their incredible potential?

Synthetic Biology: Making Life from Bits and Pieces
Scientists are combining biology and engineering to change the world.

PRIMARY LITERATURE

Controlling the formation of bacterial biofilms
Antitoxin MqsA helps mediate the bacterial general stress response.
View | Download

The memory of iPS cells
Incomplete DNA methylation underlies a transcriptional memory of somatic cells in human iPS cells.
View | Download

Mitochondria change shape to help the cell survive
During autophagy mitochondria elongate, are spared from degradation and sustain cell viability.
View | Download

An artificial self-assembling retina from stem cells
Self-organizing optic-cup morphogenesis in three-dimensional culture.
View | Download

Classic paper: T cells mediate immunity through MHC restriction (1974)
Restriction of *in vitro* T cell-mediated cytotoxicity in lymphocytic choriomeningitis within a syngeneic or semiallogeneic system.
View | Download

SCIENCE ON THE WEB

No Microscope Needed
View images from different types of microscopes at different magnifications

Nature Supplement: Cellular Imaging Techniques
How do we observe living cells?

How Small?
See the difference between a coffee bean and a single atom.

Cell Theory

The nature of living tissue was a mystery to early scientists. Then, in 1665, Robert Hooke became the first person to see and name biological cells.

What is cell theory?

Hooke used a simple microscope to look at cork, a dead layer of cells in tree bark. He noticed that cork was made of small, uniform units (Figure 1). Hooke thought these units looked like little rooms so he named them "cells," from the Latin word *cella* for "little room." By the mid-1800s, scientists had observed cells in a wide variety of tissues from living organisms through their microscopes. Based on these observations, scientists concluded that all organisms are made up of one or more cells.

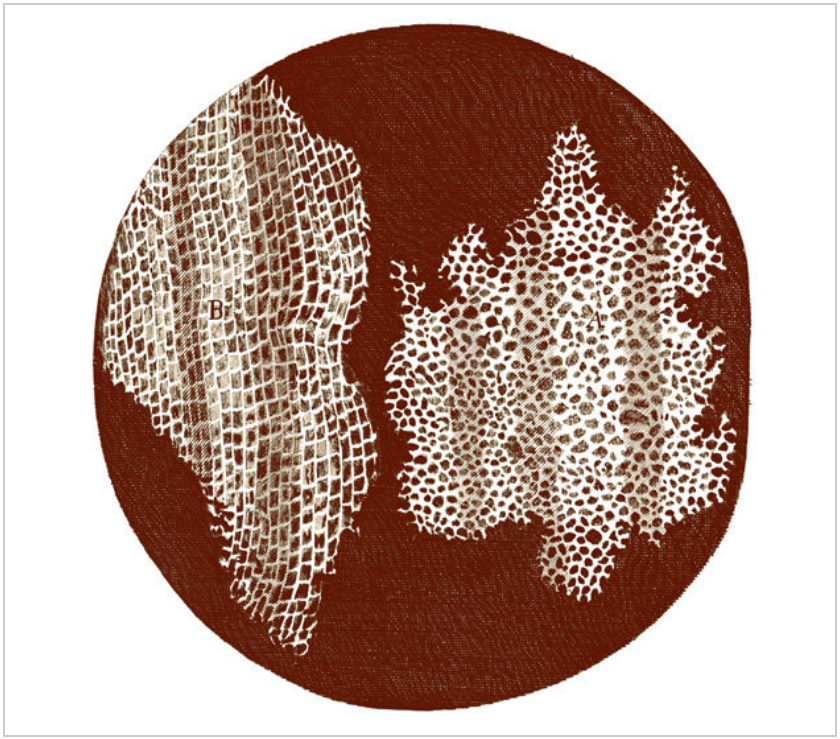


Figure 1: Robert Hooke's drawing of cork from the bark of a cork oak tree.
In the late 1660s, Hooke noticed that plants were composed of repeating units that he called "cells." Hooke's observation marked the beginning of biological cell theory.
Originally published by Robert Hooke in *Micrographia*. London: Royal Society Press, 1665.

Studies by early scientists such as Hooke were the first steps in the discovery of how cells work. Today, the results of this research are summarized in modern cell theory. Cell theory has two main parts:

1. Cells are the basic unit of life. All living organisms are composed of at least one cell; and the chemical reactions needed for life (such as cellular respiration) happen inside these cells.
2. Cells come from other cells. New cells are made when one cell copies its DNA and divides, distributing an identical copy of the DNA to each new cell.

Why aren't there giant cells?

Cells are very small. Most cells are less than 100 microns (micrometer or μm; 10^{-6} m) across — too small to see with the naked eye. Why are cells so small? The ratio of the surface area to volume decreases with increasing cell size (Figure 2). In other words, the relative surface area of the membrane decreases as the cell becomes bigger. Cells need to move nutrients into the cell and waste products back out. Because of its larger volume, a bigger cell has relatively less membrane surface area across which materials can move into and out of the cell. If the cell gets large enough, there is too little surface area to absorb the greater quantities of nutrients needed, and the cell's surface cannot expel all of the waste that the cell produces. Because of this, cell size is typically limited to less than 500 microns. Some cells that must transport large amounts of substances across their membrane have evolved adaptations to maximize surface area. For example, the cell membrane of a mammalian intestinal cell has numerous projections (called microvilli) allowing increased absorption of nutrients.

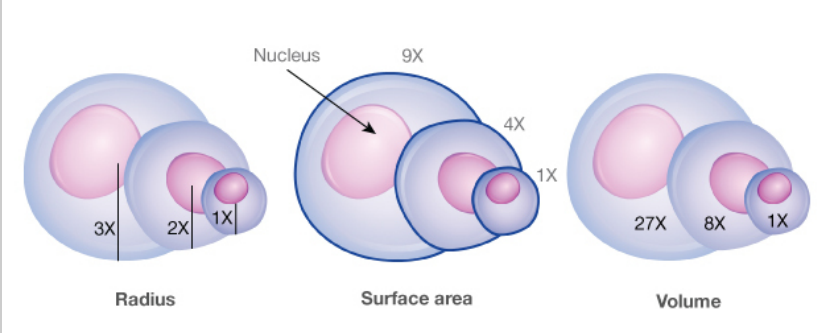


Figure 2: The relationship between surface area and volume with increasing cell size.

As a spherical cell increases in size, its radius increases. The surface area of a sphere is calculated with the formula $4\pi r^2$, and the volume of a sphere is calculated with the formula $4/3\pi r^3$, where r represents the radius of the sphere. Notice that surface area and volume both increase as the cell grows bigger, but the volume increases much faster than the surface area.

Let's calculate how surface area and volume change with increasing cell size. For this example, consider a cube-shaped cell. The surface area of a cube is equal to its length multiplied by its width multiplied by its six sides (L×W×6). How do scientists calculate the volume of a cube? The volume of a cube is equal to its length multiplied by its width multiplied by its height (L×W×H).

Notice that as the cube gets bigger, the ratio of surface area to volume decreases. This is the same trend as occurs in a sphere, as shown in Figure 2. That is, volume increases faster than surface area. Thus, bigger cells have less surface area per unit volume to transport materials into and out of the cell.

Length of one side	Surface area	Volume	Surface area: Volume
1 mm	6 mm²	1 mm³	6:1
2 mm	? mm²	? mm³	3:1
4 mm	? mm²	? mm³	1.5:1

Table 1: Ratios of surface area to volume for three cubes.

Test Yourself

Calculate the following surface areas and volumes for cubes with side lengths of 2 mm and 4 mm to complete Table 1 (fill in the missing information in Table 1 marked as "?"). Please label your answers 1–4:1. The surface area of a cube with a side length of 2 mm.2. The volume of a cube with a side length of 2 mm.3. The surface area of a cube with a side length of 4 mm.4. The volume of a cube with a side length of 4 mm.

Submit

Exceptions to the rule.

Egg cells and some single-celled organisms are more than 500 microns in diameter and are visible to the naked eye. The giant squid neuron (a nerve cell) is almost a meter in length. How can cells this big exist? Cells have strategies at their disposal to solve the problem of the surface area to volume ratio. Egg cells are mostly metabolically inactive. They need few nutrients and produce little waste. Nerve cells are long and thin so that all parts of the cell are close to the plasma membrane. Other cells create folds in their plasma membranes to increase surface area.

Multicellular organisms have evolved more than once during the evolutionary history of life. There are a couple of advantages to an organism being multicellular. First, because of limitations on cell size, a multicellular organism can be much larger than a single-celled organism. Large size has advantages. For example, a multicellular plant can absorb nutrients through underground roots while its leaves utilize the energy from sunlight to produce sugar. Second, in a multicellular organism cells can become specialized in function. For example, in our bodies, some cells protect us from the outside environment (e.g., skin and immune cells), other cells specialize in digestion and waste processing, other cells specialize in reproduction, and so on. It is such cellular specialization that makes possible the variety and complexity of life as we experience it.

How big are cells?

What is the smallest thing visible to human eyes? Human vision allows people to see objects as small as the period at the end of this sentence. People with good eyesight can see even smaller objects. Most plant and animal cells are about 10 to 100 microns across and therefore invisible to human eyes; however, objects of this size are easily seen with a light microscope. Powerful light microscopes allow the user to detect some detail, such as the cell nucleus and other large organelles, and still more detail can be seen with an electron microscope. Most bacterial cells range from about 1 to 10 microns long. Seeing these cells requires a relatively good light microscope, and details can only be seen with an electron microscope (Figure 3).

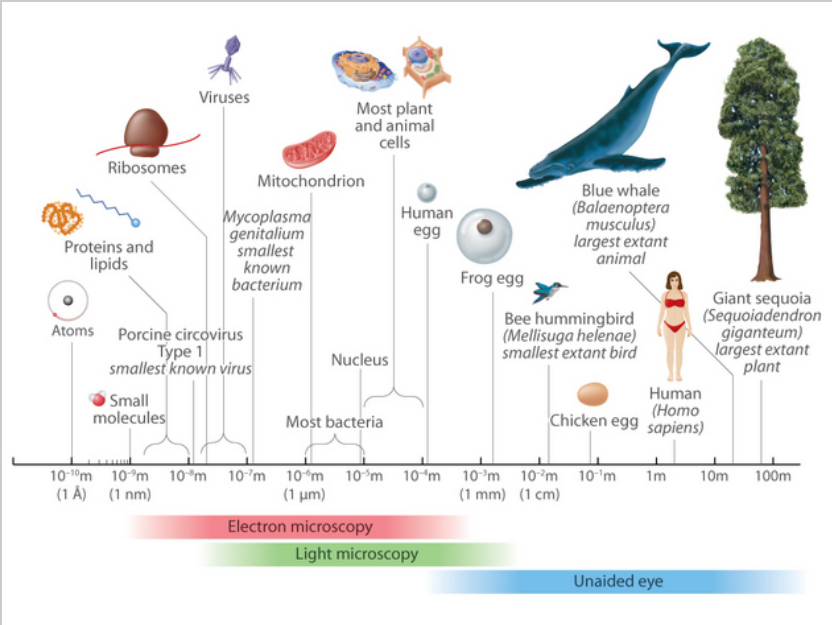


Figure 3 : The size of biological components.
Notice that the scale on the image is a logarithmic scale, which means that numbers are increasing in orders of magnitude.

If cells are so small, how can we see them?

The science of cell biology began when scientists such as Robert Hooke used microscopes to look at tissues and microorganisms. The first microscopes were little more than refined magnifying glasses. Scientists could see relatively large cells with these instruments, but small cells were beyond their capability. Today we have powerful light microscopes with which we can see very small cells. Using electron microscopes scientists can see these cells in greater detail, and they can also obtain images of viruses and large macromolecules. Such advances in microscopy push the boundaries of our knowledge. Ever more powerful microscopes are helping scientists to model dynamic cell processes as well as details of intricate structures.

How do microscopes work? Through the process of **magnification**, microscopes make objects look bigger. Another important parameter in microscopy is **resolution**. Resolution is the ability of a microscope to distinguish two separate points (Figure 4). Under low resolution, two separate objects appear to be a single point. Under higher resolution, the two objects can be distinguished.

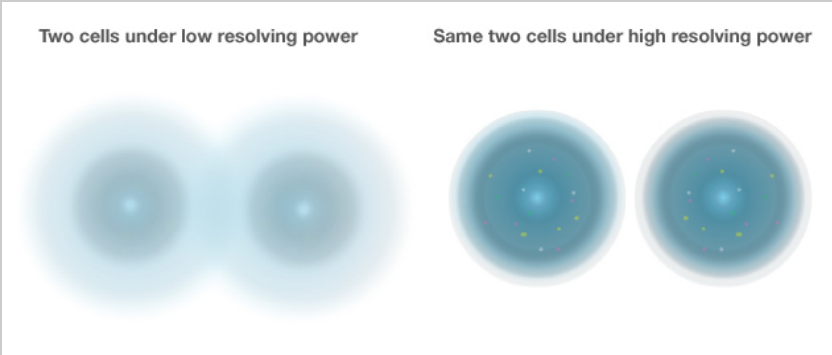


Figure 4: Resolving power matters.
The resolving power of a microscope determines whether you can distinguish two points, such as the difference between one cell and

another. Microscopes with high resolving power will be able to distinguish points as separate, whereas microscopes with low resolving power will blur two points.

A third important parameter in microscopy is **contrast**, the ability to distinguish an object from the background. Many cells and their component parts are difficult to see because they appear clear. One way that scientists can solve this problem is by staining cells and the **organelles** inside them. Staining increases contrast, emphasizing the color or tone difference between objects and the background. Some types of microscopes exaggerate differences in density to increase contrast and improve the visibility of specimens.

The two basic types of microscopes are light microscopes and electron microscopes. Each type of microscope has its uses and limitations. Light microscopes work by shining light on or through the object. Optical lenses magnify the image. Many biology labs have light microscopes, which are relatively inexpensive and easy to use. However, the resolution of light microscopes is limited by the wavelength of visible light. If an object is smaller than a wavelength of visible light, it becomes impossible to resolve with a light microscope. Electron microscopes overcome this limitation because they use electrons rather than light. The wavelength of the electron beam is much shorter than wavelengths of visible light. This lets us resolve objects that are much smaller (Figure 5). But electron microscopes are expensive and bulky. Also, we cannot use them to look at living cells as we can with most light microscopes.

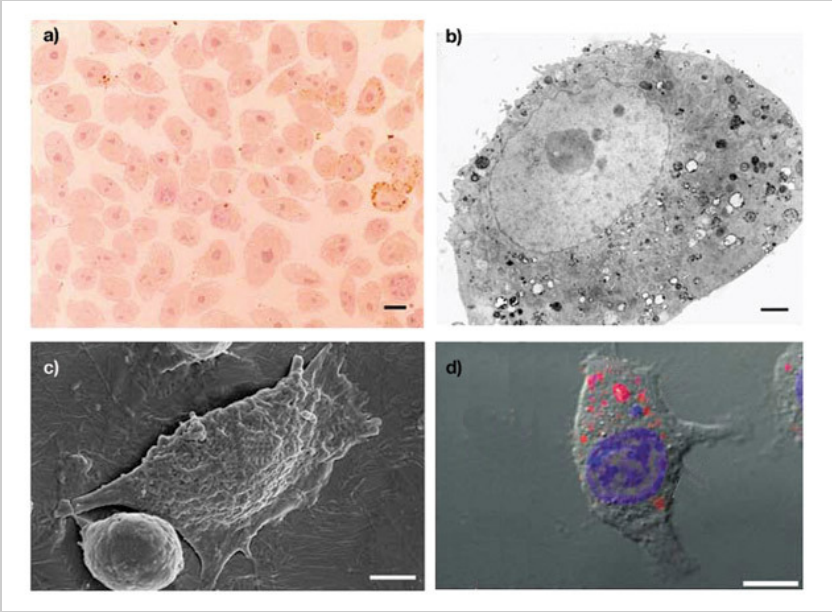


Figure 5: Types of microscopic images.
A series of micrographs of white blood cells (macrophages) using different microscopy techniques. Panel a): light microscopy (bright-field microscopy), scale bar = 10 µm; panel b) transmission electron microscopy (TEM), scale bar = 1 µm; panel c) scanning electron microscopy (SEM), scale bar = 2 µm; panel d) light microscopy using fluorescent labeling (fluorescence microscopy) of subcellular structures in red and purple, scale bar = 8 µm.

The most common light microscopy is **bright-field microscopy**, which shines light through the sample and magnifies the image with a series of lenses. Early microscopes used one or two lenses. Most microscopes today have a pair of ocular lenses, which provide a stereoscopic image, and three or more objective lenses of different magnifications. Bright-field microscopes work well for many applications, including undergraduate teaching, but unless specimens are naturally pigmented or are stained (which often kills the cells), the lack of contrast hinders the ability to view the sample. Hence, cell biologists have developed variations of the light microscope that increase resolution and contrast.

Most modern microscopes can be adjusted to allow the use of different lighting techniques that enhance a sample or highlight desired features. The choice of a particular technique depends on the information desired. One method might obscure detail in order to emphasize other features. **Dark-field microscopy** increases contrast. In this method, light scattered by the object is refocused so that it can be viewed through the objective lens. Light that passes directly through the object is blocked, so the background appears dark. As a result, the specimen appears brightly lit on a dark background. **Phase-contrast microscopy** also increases contrast. This technique takes advantage of the fact that when light passes through an object, its light waves become shifted relative to the light waves passing through air. How much the light is shifted depends on the density of the object. The human eye cannot detect phase shifts, so a phase-contrast microscope converts the difference in phase to differences in brightness, or contrast. Because cellular components have different densities, phase contrast microscopy can distinguish between these components. Both the dark-field and phase contrast microscopes are able to increase contrast in a cell without staining it, which improves the images of living cells.

Fluorescence microscopy requires special fluorescent stains that make visible features that cannot be seen with other microscopy techniques. Fluorescent probes are sometimes linked to a specific macromolecule so that its localization in the cell can be determined. For example, a protein can be flagged with a green fluorescent probe and injected in a cell. The scientist then observes which parts of the cell glow green to determine the localization of the protein. **Confocal microscopy** uses laser light to illuminate a fluorescently labeled sample. Scientists can view cells one slice at a time. The images from each slice are then reconstructed to form a three-dimensional image.

Test Yourself

Compare and contrast light and electron microscopes.

Submit

The techniques of the light microscope are limited in resolution because they use lenses to focus light waves. Electron microscopes (EMs) use magnets to focus electrons on a specimen. The physics is similar in principle to how light microscopes focus light using lenses. However, a computer translates the electron beam into an image because electrons are not visible to the eye. The main drawback to electron microscopes is that samples must be killed and preserved because the electrons must travel through a vacuum. However, electron micrographs image objects that are much smaller than what we can see with a light microscope. This capability has driven major advances in our knowledge of sub-cellular structure and function.

If a specimen is sliced very thin, electrons can travel right through it. This

technique is used in **transmission electron microscopy (TEM)**. It lets us see internal cellular components clearly. **Scanning electron microscopy (SEM)** coats the specimen with a metal that causes electrons to be deflected off the surface. The image produced informs us about the surface structures of a cell.

Future perspectives.

What can we image with new and more powerful microscopes? There are remarkable and powerful new imaging methods that take advantage of sophisticated optics, lasers and massive computing power. Two of these methods are scanning tunneling microscopy and confocal microscopy. Scanning tunneling microscopes take advantage of an odd phenomenon called quantum tunneling. In quantum tunneling, one object passes through another object that normally would block it. Quantum tunneling never happens with large objects (if it did, when you ran at a brick wall, sometimes you would pass through). However, quantum tunneling does happen to subatomic particles. In scanning tunneling microscopy, a very fine tip is placed near the surface of an object. Sometimes, electrons pass from the object to the tip through quantum tunneling. Passage of electrons into the tip produces a current. Thus, the probe can detect the position of individual atoms by measuring the current produced. This current map is converted by software into images that we can see.

Another approach researchers have developed is confocal microscopy, which is a technique for reducing the image degradation that occurs because out-of-focus light obscures what one sees through a microscope. The technique works by limiting the amount of light that passes through an aperture to the light rays that are in focus. Then by scanning the sample in either two or three dimensions, a computer can reconstruct a highly detailed image. Other advances have improved on the fluorescence microscope and the bright-field microscope. In 1665, Robert Hooke saw biological cells through a simple microscope for the first time, and this technique profoundly changed our understanding of the world around us. Who knows what we will see and learn as we build microscopes with enhanced resolution and magnification?

WHY DOES THIS TOPIC MATTER?


Stem Cells
Stem cells are powerful tools in biology and medicine. What can scientists do with these cells and their incredible potential?


Synthetic Biology: Making Life from Bits and Pieces
Scientists are combining biology and engineering to change the world.

PRIMARY LITERATURE

Controlling the formation of bacterial biofilms
Antitoxin MqsA helps mediate the bacterial general stress response.
View | Download

The memory of iPS cells
Incomplete DNA methylation underlies a transcriptional memory of somatic cells in human iPS cells.

View | Download

Mitochondria change shape to help the cell survive
During autophagy mitochondria elongate, are spared from degradation and sustain cell viability.
View | Download

An artificial self-assembling retina from stem cells
Self-organizing optic-cup morphogenesis in three-dimensional culture.
View | Download

Classic paper: T cells mediate immunity through MHC restriction (1974)
Restriction of *in vitro* T cell-mediated cytotoxicity in lymphocytic choriomeningitis within a syngeneic or semiallogeneic system.
View | Download

SCIENCE ON THE WEB

No Microscope Needed
View images from different types of microscopes at different magnifications

Nature Supplement: Cellular Imaging Techniques
How do we observe living cells?

How Small?
See the difference between a coffee bean and a single atom.

Cell Types

Cell theory states that all living things are made of one or more cells. But what is a cell? All cells share four basic functions. First, cells separate their internal environment from the external environment in order to maintain **homeostasis**. This is the function of the plasma membrane. A light microscope allows scientists to see the plasma membrane as a line on the outside of the cell. The **plasma membrane** is a phospholipid bilayer that contains proteins and other components such as the lipid cholesterol. Think of the membrane as the cell's gatekeeper. It controls much of what goes into and out of the cell. Second, cells must store information and pass it on to the next generation. This is the function of **DNA**, which contains the information for building proteins. Third, cells must be able to build proteins. This function is achieved by ribosomes. Proteins then build other cellular components. Fourth, cells must conduct the chemical processes of life. Many of these chemical reactions occur in the **cytoplasm**. The medium for chemical process is the semifluid matrix of the cell, called the **cytosol**.

The similarities shared by all cells are necessary for living organisms to survive. The differences between cells allow for the diversity of life. There are three domains of life: Archaea, Bacteria, and Eukarya, each with a distinct cell type. The domains Archaea and Bacteria used to be classified as a single group, but genetic analyses showed that these types of cells are distinct. The domains differ in the details of their cellular chemistry. For example, archaea cells have a plasma membrane but the lipids comprising the membrane are chemically very different from the phospholipid bilayer in Bacteria. In this section we will focus on cell structures.

Archaea, Bacteria, and Eukarya cells share similar basic functions and structures.

As living organisms, Archaea, Bacteria, and Eukarya share the same basic needs. They must ingest food, expel waste and reproduce. All cells must replicate their DNA to reproduce. They make proteins from an RNA template using ribosomes. The cytoplasm is enclosed within a lipid membrane though the composition of this membrane differs among the domains. The three domains of life share these features because they have been conserved throughout the course of evolution. The similarities of biochemistry at this very basic level support the hypothesis that cells derive from a common ancestor. In turn, the vast array of cell types has arisen due to evolution through countless selective events and subsequent adaptation.

What is the difference between prokaryotic and eukaryotic cells?

How does cellular structure help scientists categorize and classify life? Biologists group Archaea and Bacteria into the prokaryote category. **Prokaryotes** are characterized as lacking membrane-enclosed organelles, such as a nucleus. Cells that do not have a nucleus are called **prokaryotic** (Figure 6). On the other hand, humans, redwood trees and algae are all classified as **eukaryotes** because their cells possess membrane-enclosed organelles. Cells that have a nucleus are called **eukaryotic** (Figure 7). With this major classification of organisms, humans and algae are actually more like each other than Archaea and Bacteria (major prokaryotic groups) are to each other. Eukaryotic cells tend to be relatively larger than prokaryotic cells. The root *-karyote* derives from the Greek word for "kernel" and refers to the cell nucleus, which resembles a kernel of corn. The root *eu-* comes from the word for "good" or "true." Thus, *eukaryote* means true nucleus and refers to

cells that have a nucleus, namely eukaryotic cells. Prokaryotes, on the other hand, do not have a nucleus. The root *pro-* derives from "before" in Greek. Thus, *prokaryote* in essence means "before the nucleus." Prokaryotic cells lack a true nucleus surrounding their DNA because their evolution preceded the evolution of the nucleus approximately 2.1 billion years ago.

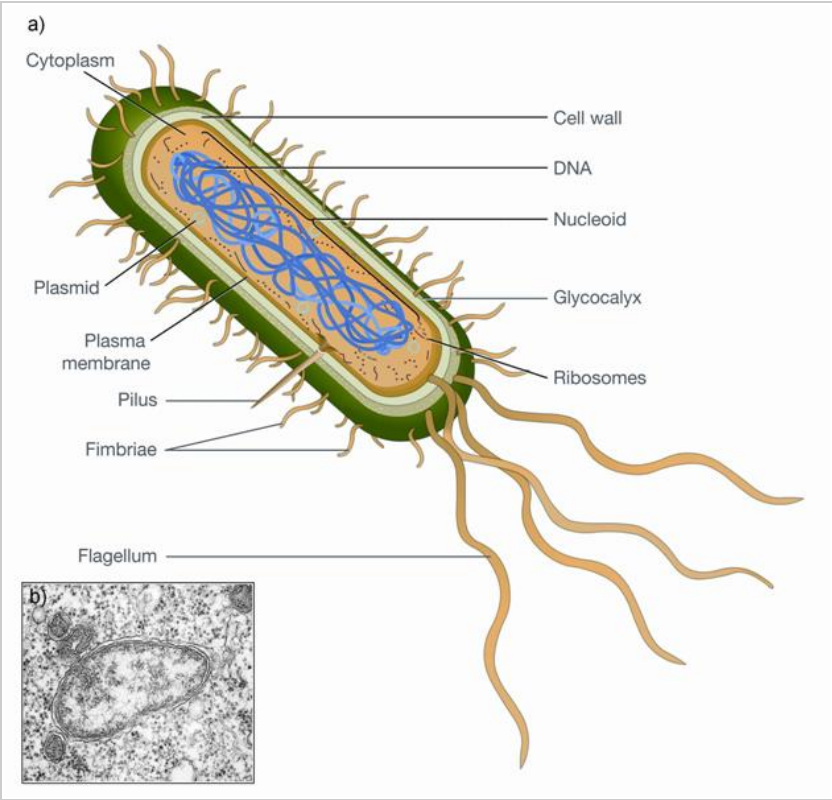


Figure 6: The basic structure of a prokaryotic cell.
All cells have DNA, a plasma membrane, and cytoplasm. Besides these features cellular diversity is characterized by the presence or lack of internal structures. Prokaryotic cells lack a nucleus and membrane-enclosed organelles. a) Displays the major structures in a typical prokaryotic cell. b) Transmission electron micrograph of a prokaryotic cell that is enclosed within a vacuole of a eukaryotic cell. What structures can you identify? (Original size: 2 microns)

Figure Detail

Cell size is one way to distinguish between prokaryotic and eukaryotic cells. Eukaryotic cells are typically about 10 times larger than prokaryotic cells. Students using the light microscopes in most biology classrooms can easily see eukaryotic cells, while prokaryotic cells appear as tiny specks. More powerful light microscopes and electron microscopes allow distinct areas or structures to be seen in eukaryotic cells. These organized structures within the cell are organelles, which have a variety of specialized functions. In plant cells, the chloroplast is the site for photosynthesis, which converts light energy into chemical energy. Organelles compartmentalize cellular structures and function, allowing eukaryotic cells to be larger. Think of departments in a large company — division of labor allows for greater corporate structure. The lack of organelles does not mean that prokaryotes are simpler cells. They just have a different organization. Prokaryotic cells carry out photosynthesis

without chloroplasts, and carry out aerobic respiration without mitochondria. In fact, prokaryotes have many more metabolic options than eukaryotic cells do. Purple sulfur bacteria, for example, use a type of photosynthesis that does not produce oxygen. Other prokaryotes metabolize unusual substrates such as methane and hydrogen sulfide. Prokaryotes use many chemical processes not encountered among eukaryotes. This diversity of metabolic processes is a reflection of their origins during Earth's early history when the environment was much different than it is today.

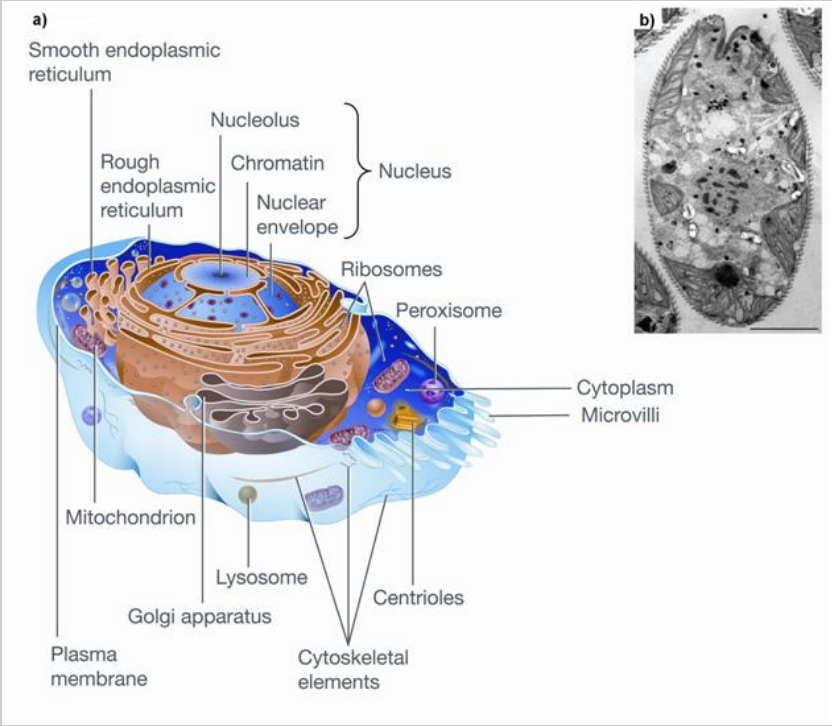


Figure 7: The basic structure of a eukaryotic animal cell.
Like prokaryotic cells, eukaryotic cells have DNA, a plasma membrane, and cytoplasm. In addition, eukaryotic cells have greater complexity and contain membrane-bound organelles. a) A generalized animal cell with typical structures identified. b) Transmission electron micrograph of a eukaryotic cell, *Euglena gracilis* (scale bar, 5 µm).

Figure Detail

Recent evidence suggests that large groups of prokaryotic cells may work together in a community. Studies of biofilms show that these formations are sometimes made up of groups of different species. Each species confers a benefit on the community, such as protection from the environment. Such findings point to a possible mechanism for the evolution of multicellularity and specialization of cell function within a multicellular organism. Multicellularity is believed to have evolved multiple times, beginning more than a billion years ago.

BIOSKILL

Studying Organelles

To study the carburetor of a car, a mechanic needs to do two things. Initially, the mechanic wants to understand the part's function within the engine and how it interacts with other engine parts. Eventually, however, it would be helpful to remove the carburetor and directly study its function. Scientists use a similar approach when studying organelles. Studying them while they are still functioning within the cell can provide useful information, but directly

studying them also gives us a lot of useful information. How do scientists obtain organelles out of a cell to study them directly?

The solution is cell fractionation (Figure 8). The first step is to homogenize cells in a blender. The cells break apart and release their contents, becoming cellular slurry, which is called homogenate. The various cell components have characteristic weights. For example, a ribosome is much smaller and lighter than a mitochondrion. The next step is to spin the homogenate in a centrifuge. At a relatively low speed, large, heavier items will collect in a small pellet at the bottom, and small, lighter items will remain in suspension. The pellet is removed. The sample is then spun at higher speeds, causing smaller cellular components to collect and form pellets. The pellets are collected to study the isolated organelles.

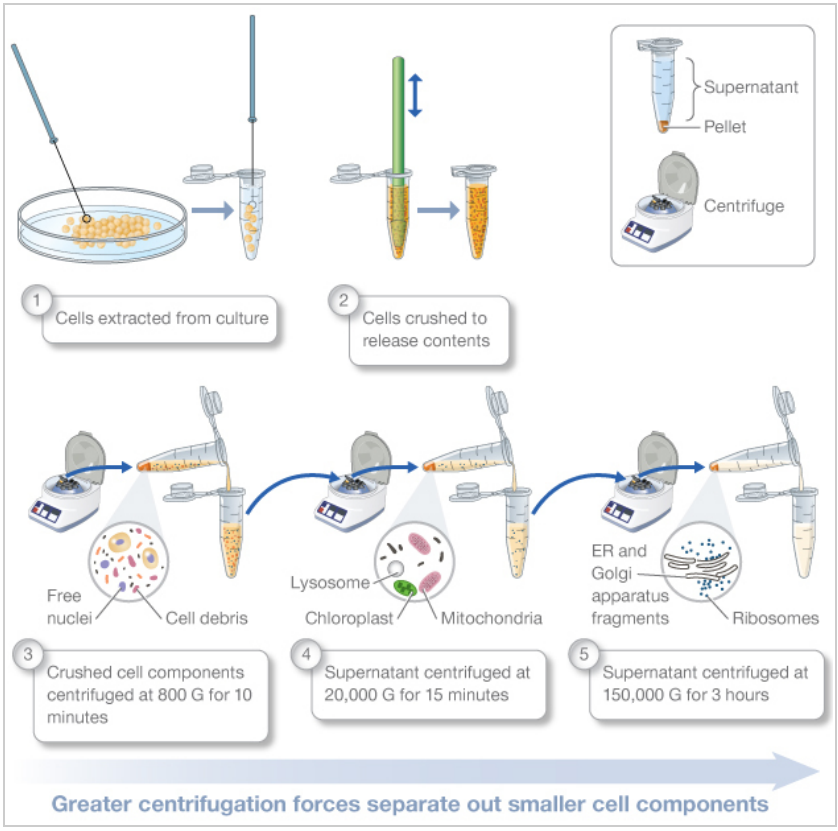


Figure 8: Cell fractionalization separates a cell's components.
Cell fractionalization is a laboratory technique used for isolating cell organelles and other cell components for study. The number of centrifugation steps needed depends on the size of the component to be isolated. Gravitational force (G) values are directly proportional to the spinning speed of the centrifuge. ER = endoplasmic reticulum.
 Figure Detail

BIOSKILL

Cellular components have unique structures and functions.

What is the nucleus and why is it important? The nucleus is where eukaryotic cells house their DNA. A double membrane called the nuclear envelope surrounds the nucleus and protects the DNA. Prokaryotic cells lack this protective layer around their DNA. Prokaryotic DNA tends to stay in a region of the cell called the **nucleoid** (nucleus-like). This region is akin to a nucleus because DNA is localized there, but because it is not protected by a membrane, it cannot be called a nucleus.

Prokaryotic DNA is organized typically into one, circular chromosome, while eukaryotic DNA is organized into many linear chromosomes. However, in

addition to their main chromosome, prokaryotes can also have numerous plasmids. **Plasmids** are small circular DNA strands that are separate from the main chromosome. The adaptive advantage of having genes in plasmids rather than the chromosome is that genetic information encoded on plasmids can easily be passed from one bacterium to another. While most of the essential genes for life are on the main bacterial chromosome, plasmids carry information for additional functions. For example, some plasmid genes confer antibiotic resistance. A plasmid with genes for antibiotic resistance is not essential for life, but a cell carrying it will be favored by selection if the cell is exposed to certain antibiotics. Bacteria transfer plasmids relatively easily among themselves, which is often how bacteria acquire antibiotic resistance, and why some diseases and infections are increasingly resistant to antibiotics. A single cell with a resistance gene on its plasmid will pass that gene on to all its offspring.

The ability to transfer plasmids between different species of bacteria is another reason antibiotic resistance can spread very quickly. Plasmids are copied and transferred to a neighboring cell via a structure called a conjugation **pilus**. Through the pilus, an antibiotic-resistant bacterium may pass on the plasmid to its neighbors, which then pass it on to their offspring and neighbors.

Although the location and organization of genetic material is different, all cells use their DNA to hold genetic instructions for building proteins. Proteins are assembled on structures called **ribosomes**. Since both prokaryotic and eukaryotic cells need to make proteins, they both have ribosomes. The three domains of life differ in the structure of their ribosomal structures, but the way ribosomes work is similar among the domains.

Cells have additional layers outside their plasma membranes. One such layer is the **cell wall**. Some eukaryotes, including plants, algae, and fungi, have cell walls. Plant and green alga cell walls are made primarily of cellulose. Fungal cell walls are made of chitin and other molecules. Most members of the Bacteria and Archaea domains possess a cell wall. Bacterial cell walls are made primarily of **peptidoglycans**, molecules formed from carbohydrates linked by peptides. Gram-positive bacteria have a single, thick cell wall. Gram-negative bacteria have a thin cell wall and a second lipid membrane outside this wall. Archaean cell walls consist of a rigid array of proteins. We are still learning about archaean cells and have incomplete knowledge of their cell wall structure. Animal and protozoan cells do not possess a cell wall, but a complex structure called the **extracellular matrix** surrounds the cell.

Some bacteria and eukaryotes have yet another layer outside of the cell wall called the glycocalyx. The root *-calyx* means "outer covering," while *glycol-* means "sweet." So in a manner of speaking, these cells are sugarcoated. The **glycocalyx** is a carbohydrate-based outer covering that protects the cell. In bacteria, the glycocalyx also aids in the formation of biofilms.

Cells can have various projections or appendages. Many cells have **flagella**, long mobile projections used in moving the cell from one place to another. Some eukaryotic cells have short projections called **cilia**. In multicellular organisms, flagella or cilia often function to move external substances across the cell surface. Both prokaryotic and eukaryotic cells can have flagella, but they are structurally different and composed of different proteins. Prokaryotic cells often have **fimbriae**, short projections that help them attach to surfaces. Fimbriae sometimes look a bit like pili but their structure and function are very different. Pili are used to transfer plasmids from one cell to another; fimbriae are used to attach to surfaces such as an animal cell the bacterium is parasitizing.

Test Yourself

Answer the following questions to compare and contrast eukaryotic and prokaryotic cells. Please label your answers 1-6: 1. Size: Which is larger, a eukaryotic cell or a prokaryotic cell? 2. Single or multi-celled: Are eukaryotic organisms single-celled or multi-celled? Are prokaryotic organisms single-celled or multi-celled? 3. Presence of organelles: What type(s) of cells have membrane-bound organelles? 4. Location of DNA: Where is the DNA located in eukaryotic cells? Prokaryotic cells? 5. Presence of ribosomes: In what type(s) of cells are ribosomes? 6. Presence of glycocalyx: In what type(s) of cells is a glycocalyx found?

Submit

Future perspectives.

The **endosymbiotic theory** attempts to explain how eukaryotic cells evolved from prokaryotic ones. According to this theory, mitochondria originated as free-living prokaryotes that were engulfed by an ancestral eukaryotic cell. The engulfed prokaryote was not digested and developed a symbiotic, or mutually beneficial, relationship in which it provided nutrition to its host, while the host protected it from the environment. Over time, this relationship became obligatory; in other words one cell could not survive without the other. A second endosymbiotic event is believed to have given rise to chloroplasts. Several pieces of evidence support this theory. First, mitochondria and chloroplasts have DNA that is distinct from the nuclear DNA and that is circular, like bacterial DNA. Second, mitochondria and chloroplasts have ribosomes and can synthesize their own proteins. Third, mitochondria and chloroplasts are capable of dividing independently of the host cell.

We have discussed the primary cellular characteristics that illustrate differences between eukaryotic and prokaryotic cells. The field continues to be an active area of research. Despite extensive research on prokaryotes, scientists continue to find new and different species. Archaean cells are still a mystery, but one thing we do know is that they are very different and are changing our ideas on what cells are.

WHY DOES THIS TOPIC MATTER?


Stem Cells
Stem cells are powerful tools in biology and medicine. What can scientists do with these cells and their incredible potential?


Synthetic Biology: Making Life from Bits and Pieces
Scientists are combining biology and engineering to change the world.

PRIMARY LITERATURE

Controlling the formation of bacterial biofilms
Antitoxin MqsA helps mediate the bacterial general stress response.
View | Download

The memory of iPS cells
Incomplete DNA methylation underlies a transcriptional memory of somatic cells in

human iPS cells.
View | Download

Mitochondria change shape to help the cell survive
During autophagy mitochondria elongate, are spared from degradation and sustain cell viability.
View | Download

An artificial self-assembling retina from stem cells
Self-organizing optic-cup morphogenesis in three-dimensional culture.
View | Download

Classic paper: T cells mediate immunity through MHC restriction (1974)
Restriction of *in vitro* T cell-mediated cytotoxicity in lymphocytic choriomeningitis within a syngeneic or semiallogeneic system.
View | Download

SCIENCE ON THE WEB

No Microscope Needed
View images from different types of microscopes at different magnifications

Nature Supplement: Cellular Imaging Techniques
How do we observe living cells?

How Small?
See the difference between a coffee bean and a single atom.

Summary

OBJECTIVE **Describe key elements of cell theory.**

Cell theory has two main parts. First, cells are the basic unit of life. Second, cells come from other cells. Cells have a wide variety of components that play specific roles in keeping the cell alive. All cells contain DNA, ribosomes, and cytoplasm bound inside a plasma membrane.

OBJECTIVE **Explain why cells are limited in size.**

Cell size is limited by the constraints of the cell surface area to volume ratio. As a cell increases in size, its surface area does not increase proportionately to its increase in volume. Cells need to move nutrients into the cell and excrete waste products back out. Cells larger than 500 microns typically do not have enough surface area to maintain cell function.

OBJECTIVE **Compare and contrast light and electron microscopes.**

Light microscopes work by shining light on or through an object and use optical lenses to magnify the image. The resolution of light microscopes is limited by the wavelength of visible light. Electron microscopes overcome this limitation because they use electrons and magnets rather than light and lenses. The wavelength of the electron beam is much shorter than that of light, allowing us to see objects that are much smaller at a higher resolution. Electron microscopes are expensive and bulky, and we cannot use them to look at living cells as we can with most light microscopes.

OBJECTIVE **Compare and contrast eukaryotic and prokaryotic cells.**

Eukaryotic cells tend to be relatively large. Prokaryotic cells are much smaller and do not contain a nucleus or membrane-bound organelles. In multicellular organisms, eukaryote cells specialize to perform unique functions to ensure the organism's survival and reproduction. The endosymbiotic theory suggests that some eukaryotic membrane-bound organelles, including mitochondria and chloroplasts, arose as a result of symbioses between early prokaryotes and eukaryotes.

OBJECTIVE **Identify and discuss functions of prokaryotic cellular structures.**

Prokaryotic cell structures include the chromosome, which is localized in the nucleoid; ribosomes, where DNA is translated into proteins; plasmids, circular pieces of DNA that confer additional function; the plasma membrane and cell wall; pili, which allow transfer of DNA between individual cells; and the flagellum, which provides motility.

Key Terms

bright-field microscopy
Shines light through sample and magnifies the image with a series of lenses.

cell theory
Theory that all living organisms are made up of one or more cells and that cells are derived from other cells.

cell wall
Rigid, structural cell component that is outside the plasma membrane in plant and some other cells.

cilia
Short, mobile projections on the outer surface of a cell that are used for cell

motility or to move materials across cell surface.

confocal microscopy
Uses laser light to illuminate a fluorescently labeled sample.

contrast
Emphasis of tone or color differences between different parts of an object and between an object and the background.

cytoplasm
The interior of a cell.

cytosol
The semifluid matrix of the cell.

dark-field microscopy
In this method, light scattered by the object is refocused so that it can be viewed through the objective lens. Light that passes directly through the object is blocked, so the background appears dark.

deoxyribonucleic acid (DNA)
The primary molecule of inheritance in all cells; a double-stranded nucleic acid containing nucleotides that contain deoxyribose.

endosymbiotic theory
Widely accepted theory that states mitochondria and chloroplasts were once free-living prokaryotes prior to incorporation inside cells.

eukaryote
A major cell type defined by the presence of a nuclear membrane and membrane-bound organelles.

eukaryotic
Refers to a cell with a nucleus and membrane-bound organelles.

extracellular matrix (ECM)
Complex of proteins and carbohydrates that surrounds the cell in animals.

fimbriae
Short projections found in bacteria used to attach to surfaces.

flagellum
Long, whip-like tail used for movement.

fluorescence microscopy
Type of light microscopy that uses special fluorescent stains to make objects visible that are not visible through other microscopy techniques.

glycocalyx
Polymeric material used by some prokaryotic and eukaryotic cell types for protection. Bacteria use the glycocalyx to form a biofilm.

homeostasis
Animal's ability to adjust and modify its cellular processes in order to maintain a relatively constant internal environment or equilibrium.

magnification
The ability to make objects appear larger.

nucleoid
The specific region in the cytoplasm of a prokaryotic cell where genetic material is stored.

organelle
Organized, membrane-bound structure in eukaryotic cell having a specialized function or functions.

peptidoglycan
Molecule composed of carbohydrates (polysaccharides) linked by polypeptides; a major component of cell walls in bacteria.

phase-contrast microscopy
When light passes through an object, the light waves become shifted. The denser the object, the more shifted the waves become. A phase-contrast microscope converts the phase shift into differences in brightness, or contrast, that the human

eye can detect.

pilus
Connection between two prokaryotic cells through which plasmids can be transferred.

plasma membrane
Serves as barrier between the living cell and outside environment; composed of phospholipid bilayer containing proteins and other components.

plasmid
A small, circular piece of DNA outside the bacterial chromosome; can carry antibiotic resistance genes.

prokaryote
A type of cell which lacks a nucleus and membrane-bound organelles.

prokaryotic
Refers to a cell that lacks a nucleus and membrane-bound organelles.

resolution
The ability to distinguish two points that are close together.

ribosome
Protein-producing factories of the cell; protein-RNA complex that facilitates the interaction of mRNA and tRNA.

scanning electron microscopy (SEM)
Specimen coated with metal that causes electrons to bounce off surface; allows viewing of surface details.

transmission electron microscopy (TEM)
Electrons passed through thin slices of specimen. Allows detailed view of internal structure.

WHY DOES THIS TOPIC MATTER?


Stem Cells
Stem cells are powerful tools in biology and medicine. What can scientists do with these cells and their incredible potential?


Synthetic Biology: Making Life from Bits and Pieces
Scientists are combining biology and engineering to change the world.

PRIMARY LITERATURE

Controlling the formation of bacterial biofilms
Antitoxin MqsA helps mediate the bacterial general stress response.
View | Download

The memory of iPS cells
Incomplete DNA methylation underlies a transcriptional memory of somatic cells in human iPS cells.
View | Download

Mitochondria change shape to help the cell survive
During autophagy mitochondria elongate, are spared from degradation and sustain cell viability.
View | Download

An artificial self-assembling retina from stem cells
Self-organizing optic-cup morphogenesis in three-dimensional culture.
View | Download

Classic paper: T cells mediate immunity through MHC restriction (1974)
Restriction of *in vitro* T cell-mediated cytotoxicity in lymphocytic choriomeningitis within a syngeneic or semiallogeneic system.
View | Download

SCIENCE ON THE WEB

No Microscope Needed
View images from different types of microscopes at different magnifications

Nature Supplement: Cellular Imaging Techniques
How do we observe living cells?

How Small?
See the difference between a coffee bean and a single atom.

Test Your Knowledge

1. Which of the following is NOT a part of cell theory?

- Cells carry out the basic chemical reactions needed for life.
- Cells are the basic unit of life.
- Every living organism is made up of many cells.
- All living organisms are made of one or more cells.
- All cells come from other cells.

2. Complete the following sentence: The resolution of a microscope is defined as its...

- ability to distinguish between the specimen and the background.
- ability to distinguish between two adjacent points.
- ability to view small objects.
- ability to magnify specimens.
- All answers are correct.

3. Viruses are able to cause disease in living organisms. However, viruses are not made of cells. What does this mean?

- Viruses must be living because they interact with living organisms.
- Viruses must be living because they replicate.
- Viruses must not be alive because they are not made of cells.
- The cell theory must be wrong.
- Viruses must contain cells.

4. Which of these is NOT a true statement?

- All cells contain cytoplasm.
- All cells contain DNA.
- All cells have plasma membranes.
- All cells contain mitochondria.
- All cells contain ribosomes.

5. Which of the following is found in eukaryotic cells but not in prokaryotic cells?

- a nucleus
- a cell membrane
- DNA
- enzymes
- a cell wall

6. Which of the following is NOT true of most or all multicellular organisms?

- Multicellular organisms are typically larger than unicellular organisms.
- Multicellular organisms have tissues with specialized functions.
- Multicellular organisms have specialized reproductive cells.
- Multicellular organisms have a greater diversity of cell types.
- Each cell in a multicellular organism can reproduce to form a new multicellular individual.

Submit

IN THIS MODULE

WHY DOES THIS TOPIC MATTER?


Stem Cells
Stem cells are powerful tools in biology and medicine. What can scientists do with these cells and their incredible potential?


Synthetic Biology: Making Life from Bits and Pieces
Scientists are combining biology and engineering to change the world.

PRIMARY LITERATURE

Controlling the formation of bacterial biofilms
Antitoxin MqsA helps mediate the bacterial general stress response.
View | Download

The memory of iPS cells
Incomplete DNA methylation underlies a transcriptional memory of somatic cells in human iPS cells.
View | Download

Mitochondria change shape to help the cell survive
During autophagy mitochondria elongate, are spared from degradation and sustain cell viability.
View | Download

An artificial self-assembling retina from stem cells
Self-organizing optic-cup morphogenesis in three-dimensional culture.
View | Download

Classic paper: T cells mediate immunity through MHC restriction (1974)
Restriction of *in vitro* T cell-mediated cytotoxicity in lymphocytic choriomeningitis within a syngeneic or semiallogeneic system.
View | Download

SCIENCE ON THE WEB

No Microscope Needed
View images from different types of microscopes at different magnifications

Nature Supplement: Cellular Imaging Techniques
How do we observe living cells?

How Small?
See the difference between a coffee bean and a single atom.