Essentials of Cell Biology

What do an amoeba and an elephant have in common? If liver cells have the same DNA as brain cells, why are they different? What goes wrong during cancer? The answers to these questions depend on the properties of cells, the fundamental units of life. *Essentials of Cell Biology* introduces readers to the core concepts of cell biology. This course can provide an introduction to cell biology for beginning students of all ages or be a springboard to more specialized topics for advanced students. The course begins with a discussion of the fundamental properties of cells: the origin of the cell, how cells are organized, how they reproduce, and how they use energy. Other units in the course expand these topics and provide insight into the processes that regulate cell function and generate the amazing variety of cell types seen in living organisms. Topics include the decoding process that produces distinct sets of proteins in different cell types, the cellular structures responsible for cell function, the signals that cells use to communicate with one another, and the intricate controls on cell division. At the end of each unit in this eBook there is the option to test your knowledge with twenty multiple-choice questions.

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Citation

Please cite this book as:

O'Connor, C. M. & Adams, J. U. *Essentials of Cell Biology*. Cambridge, MA: NPG Education, 2010.

VIEW CONTENTS

Essentials of Cell Biology

NEXT

Contents

+ Unit 1 What Is a Cell? What Are the Essential Characteristics of Cells?
+ Unit 2 How Do Cells Decode Genetic Information into Functional Proteins?
+ Unit 3 How Are Eukaryotic Cells Organized into Smaller Parts?
+ Unit 4 How Do Cells Sense Their Environment?
+ Unit 5 How Do Cells Know When to Divide?

NEXT

Unit 1: What Is a Cell? What Are the Essential Characteristics of Cells?

Prev Page

Next Page

What are these living units called cells? Much like mini-fiefdoms, cells have all the equipment and expertise necessary to carry out the functions of life. A cell can eat, grow, and move. It can perform necessary maintenance, recycle parts, and dispose of wastes. It can adapt to changes in its environment; and it can even replicate itself.

Despite these similarities, all cells are not equal. Some are truly self-sustaining, as with single-celled bacteria or yeast, whereas others live communally, sometimes as part of complex multicellular organisms. Cells also differ in size. Although cells can be quite large — consider a frog's egg, for example — most are too small to see with the naked eye. Indeed, the development of light microscopy was essential to man's discovery of cells.

Don't be lulled by familiar schematic drawings of oval-shaped cells, either. Real cells are three-dimensional, of course, and they exist in a variety of intricate and remarkable shapes. For instance, a single human nerve cell can be over one meter long, extending from your backbone to your big toe. Compare that with the cells that line your small intestine, which have dozens of tiny, fingerlike projections to maximize the surface area across which nutrients can pass.

But how, exactly, do cells accomplish the complex tasks of life? What tools and materials do they need? And what are the key characteristics that define a cell? This unit answers these questions and provides a basic overview of the inner workings of the cell.

In This Unit

Cells Are the Basic Units of Living Organisms

Eukaryotic Cells Possess a Nucleus and Membrane-Bound Organelles

Cell Function Depends on the Continual Uptake and Conversion of Energy

Photosynthetic Cells Capture Light Energy and Convert It to Chemical Energy

Metabolism is the Complete Set of Biochemical Reactions within a Cell

Test Your Knowledge

Essentials of Cell Biology Contents

Unit 1: What Is a Cell? What Are the Essential Characteristics of Cells?

PROGRESS 20% 40% 60% 80% 100%

1.1 Cells Are the Basic Units of Living Organisms

Prev Page
Next Page
Prev Page
Next Page

Trees in a forest, fish in a river, horseflies on a farm, lemurs in the jungle, reeds in a pond, worms in the soil — all these plants and animals are made of the building blocks we call **cells**. Like these examples, many living things consist of vast numbers of cells working in concert with one another. Other forms of life, however, are made of only a single cell, such as the many species of **bacteria** and **protozoa**. Cells, whether living on their own or as part of a multicellular organism, are usually too small to be seen without a light microscope.

Cells share many common features, yet they can look wildly different. In fact, cells have adapted over billions of years to a wide array of environments and functional roles. Nerve cells, for example, have long, thin extensions that can reach for meters and serve to transmit signals rapidly. Closely fitting, brick-shaped plant cells have a rigid outer layer that helps provide the structural support that trees and other plants require. Long, tapered muscle cells have an intrinsic stretchiness that allows them to change length within contracting and relaxing biceps.

Still, as different as these cells are, they all rely on the same basic strategies to keep the outside out, allow necessary substances in and permit others to leave, maintain their health, and replicate themselves. In fact, these traits are precisely what make a cell a cell.

What Defines a Cell?

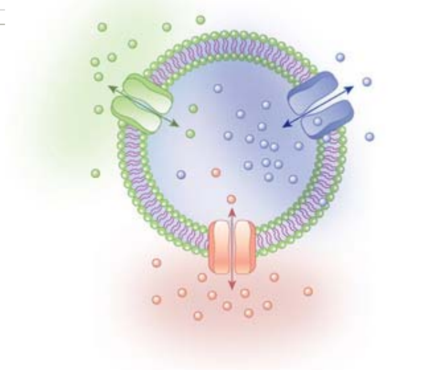

Figure 1: Transport proteins in the cell membrane
A plasma membrane is permeable to specific molecules that a cell needs. Transport proteins in the cell membrane allow for selective passage of specific molecules from the external environment. Each transport protein is specific to a certain molecule (indicated by matching colors).

Cells are considered the basic units of life in part because they come in discrete and easily recognizable packages. That's because all cells are surrounded by a structure called the **cell membrane** — which, much like the walls of a house, serves as a clear boundary between the cell's internal and external environments. The cell membrane is sometimes also referred to as the **plasma membrane**.

Cell membranes are based on a framework of fat-based molecules called **phospholipids**, which physically prevent water-loving, or hydrophilic, substances from entering or escaping the cell. These membranes are also studded with proteins that serve various functions. Some of these proteins act as gatekeepers, determining what substances can and cannot cross the membrane. Others function as markers, identifying the cell as part of the same organism or as foreign. Still others work like fasteners, binding cells together so they can function as a unit. Yet other membrane proteins serve as communicators, sending and receiving signals from neighboring cells and the environment — whether friendly or alarming (Figure 1).

Within this membrane, a cell's interior environment is water based. Called **cytoplasm**, this liquid environment is packed full of cellular machinery and structural elements. In fact, the concentrations of proteins inside a cell far outnumber those on the outside — whether the outside is ocean water (as in the case of a single-celled alga) or blood serum (as in the case of a red blood cell). Although cell membranes form natural barriers in watery environments, a cell must nonetheless expend quite a bit of energy to maintain the high concentrations of intracellular constituents necessary for its survival. Indeed, cells may use as much as 30 percent of their energy just to maintain the composition of their cytoplasm.

What Other Components Do Cells Have?

As previously mentioned, a cell's cytoplasm is home to numerous functional and structural elements. These elements exist in the form of molecules and organelles — picture them as the tools, appliances, and inner rooms of the cell. Major classes of intracellular organic molecules include nucleic acids, proteins, carbohydrates, and lipids, all of which are essential to the cell's functions.

Nucleic acids are the molecules that contain and help express a cell's genetic code. There are two major classes of nucleic acids: **deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA)**. DNA is the molecule that contains all of the information required to build and maintain the cell; RNA has several roles associated with expression of the information stored in DNA. Of course, nucleic acids alone aren't responsible for the preservation and expression of genetic material: Cells also use proteins to help replicate the genome and accomplish the profound structural changes that underlie **cell division**.

Proteins are a second type of intracellular organic molecule. These substances are made from chains of smaller molecules called **amino acids**, and they serve a variety of functions in the cell, both **catalytic** and structural. For example, proteins called **enzymes** convert cellular molecules (whether proteins, carbohydrates, lipids, or nucleic acids) into other forms that might help a cell meet its energy needs, build support structures, or pump out wastes.

Carbohydrates, the starches and sugars in cells, are another important type of organic molecule. **Simple carbohydrates** are used for the cell's immediate energy demands, whereas **complex carbohydrates** serve as intracellular energy stores. Complex carbohydrates are also found on a cell's surface, where they play a crucial role in cell recognition.

Finally, **lipids** or fat molecules are components of cell membranes — both the plasma membrane and various intracellular membranes. They are also involved in energy storage, as well as relaying signals within cells and from the bloodstream to a cell's interior (Figure 2).

Some cells also feature orderly arrangements of molecules called **organelles**. Similar to the rooms in a house, these structures are partitioned off from the rest of a cell's interior by their own intracellular membrane. Organelles contain highly technical equipment required for specific jobs within the cell. One example is the **mitochondrion** — commonly known as the cell's "power plant" — which is the organelle that holds and maintains the machinery involved in energy-producing chemical reactions (Figure 3).

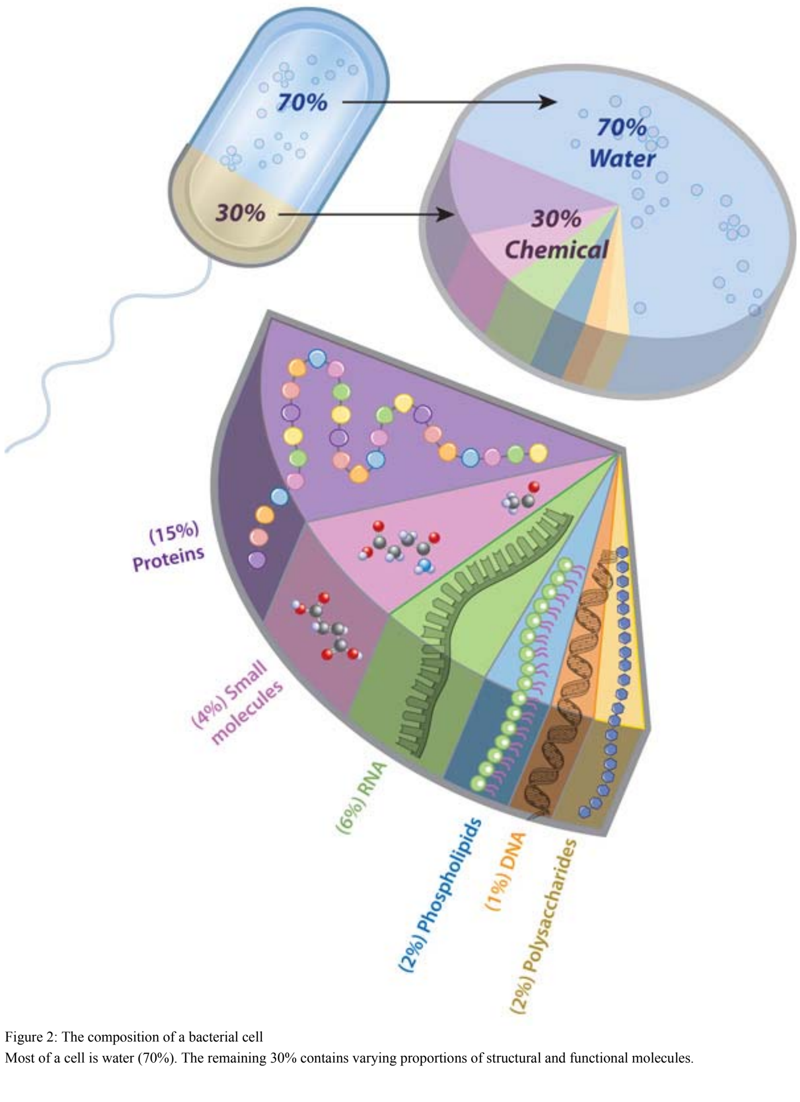

Figure 2: The composition of a bacterial cell
Most of a cell is water (70%). The remaining 30% contains varying proportions of structural and functional molecules.

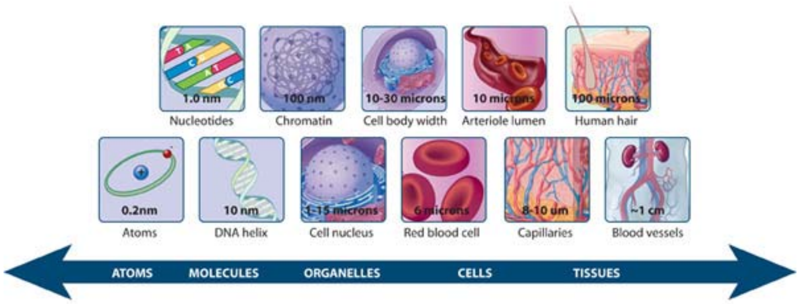

Figure 3: The relative scale of biological molecules and structures
Cells can vary between 1 micrometer (μm) and hundreds of micrometers in diameter. Within a cell, a DNA double helix is approximately 10 nanometers (nm) wide, whereas the cellular organelle called a nucleus that encloses this DNA can be approximately 1000 times bigger (about 10 μm). See how cells compare along a relative scale axis with other molecules, tissues, and biological structures (blue arrow at bottom). Note that a micrometer (μm) is also known as a micron.

What Are the Different Categories of Cells?

Rather than grouping cells by their size or shape, scientists typically categorize them by how their genetic material is packaged. If the DNA within a cell is not separated from the cytoplasm, then that cell is a **prokaryote**. All known prokaryotes, such as bacteria and **archaea**, are single cells. In contrast, if the DNA is partitioned off in its own membrane-bound room called the **nucleus**, then that cell is a **eukaryote**. Some eukaryotes, like amoebae, are free-living, single-celled entities. Other eukaryotic cells are part of multicellular organisms. For instance, all plants and animals are made of eukaryotic cells — sometimes even trillions of them (Figure 4).

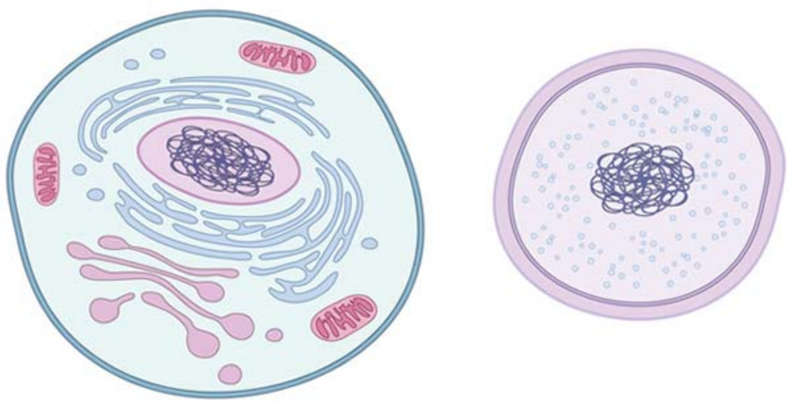

Figure 4: Comparing basic eukaryotic and prokaryotic differences
A eukaryotic cell (left) has membrane-enclosed DNA, which forms a structure called the nucleus (located at center of the eukaryotic cell; note the purple DNA enclosed in the pink nucleus). A typical eukaryotic cell also has additional membrane-bound organelles of varying shapes and sizes. In contrast, a prokaryotic cell (right) does not have membrane-bound DNA and also lacks other membrane-bound organelles as well.

How Did Cells Originate?

Researchers hypothesize that all organisms on Earth today originated from a single cell that existed some 3.5 to 3.8 billion years ago. This original cell was likely little more than a sac of small organic molecules and RNA-like material that had both informational and catalytic functions. Over time, the more stable DNA molecule **evolved** to take over the information storage function, whereas proteins, with a greater variety of structures than nucleic acids, took over the catalytic functions.
As described in the previous section, the absence or presence of a nucleus — and indeed, of all membrane-bound organelles — is important enough to be a defining feature by which cells are categorized as either prokaryotes or eukaryotes. Scientists believe that the appearance of self-contained nuclei and other organelles represents a major advance in the evolution of cells. But where did these structures come from? More than one billion years ago, some cells "ate" by engulfing objects that floated in the liquid environment in which they existed. Then, according to some theories of cellular evolution, one of the early eukaryotic cells engulfed a prokaryote, and together the two cells formed a **symbiotic** relationship. In particular, the engulfed cell began to function as an organelle within the larger eukaryotic cell that consumed it. Both chloroplasts and mitochondria, which exist in modern eukaryotic cells and still retain their own genomes, are thought to have arisen in this manner (Figure 5).

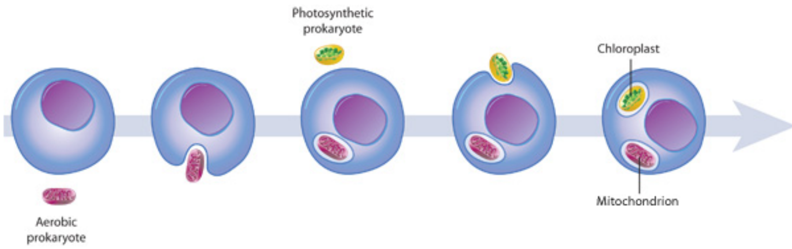

Figure 5: The origin of mitochondria and chloroplasts
Mitochondria and chloroplasts likely evolved from engulfed prokaryotes that once lived as independent organisms. At some point, a eukaryotic cell engulfed an aerobic prokaryote, which then formed an endosymbiotic relationship with the host eukaryote, gradually developing into a mitochondrion. Eukaryotic cells containing mitochondria then engulfed photosynthetic prokaryotes, which evolved to become specialized chloroplast organelles.

Of course, prokaryotic cells have continued to evolve as well. Different species of bacteria and archaea have adapted to specific environments, and these prokaryotes not only survive but thrive without having their genetic material in its own compartment. For example, certain bacterial species that live in thermal vents along the ocean floor can withstand higher temperatures than any other organisms on Earth.

Conclusion

Cells are the smallest common denominator of life. Some cells are organisms unto themselves; others are part of multicellular organisms. All cells are made from the same major classes of organic molecules: nucleic acids, proteins, carbohydrates, and lipids. In addition, cells can be placed in two major categories as a result of ancient evolutionary events: prokaryotes, with their cytoplasmic genomes, and eukaryotes, with their nuclear-encased genomes and other membrane-bound organelles. Though they are small, cells have evolved into a vast variety of shapes and sizes. Together they form tissues that themselves form organs, and eventually entire organisms.

Unit 1

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What Defines a Cell?

What Other Components Do Cells Have?

What Are the Different Categories of Cells?

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Test Your Knowledge

• View Paginated

Essentials of Cell Biology Contents

Unit 1: What Is a Cell? What Are the Essential Characteristics of Cells?

PROGRESS 20% 40% 60% 80% 100%

1.2 Eukaryotic Cells Possess a Nucleus and Membrane-Bound Organelles

Prev Page
Next Page
Prev Page
Next Page

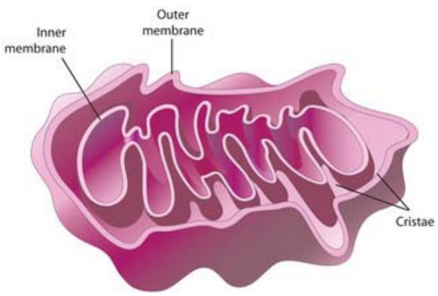

Figure 1: A mitochondrion

How do cells accomplish all their functions in such a tiny, crowded package? Eukaryotic cells — those that make up cattails and apple trees, mushrooms and dust mites, halibut and readers of Scitable — have evolved ways to partition off different functions to various locations in the cell. In fact, specialized compartments called organelles exist within eukaryotic cells for this purpose. Different organelles play different roles in the cell — for instance, mitochondria generate energy from food molecules; lysosomes break down and recycle organelles and **macromolecules**; and the endoplasmic reticulum helps build membranes and transport proteins throughout the cell. But what characteristics do all organelles have in common? And why was the development of three particular organelles — the nucleus, the **mitochondrion**, and the **chloroplast** — so essential to the evolution of present-day eukaryotes (Figure 1, Figure 2)?

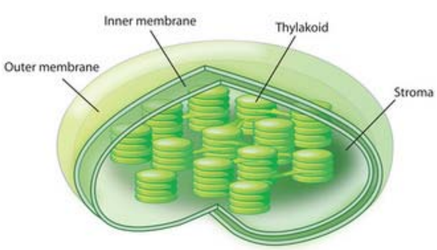

Figure 2: A chloroplast

What Defines an Organelle?

In addition to the nucleus, eukaryotic cells may contain several other types of organelles, which may include mitochondria, chloroplasts, the endoplasmic reticulum, the Golgi apparatus, and lysosomes. Each of these organelles performs a specific function critical to the cell's survival. Moreover, nearly all eukaryotic organelles are separated from the rest of the cellular space by a membrane, in much the same way that interior walls separate the rooms in a house. The membranes that surround eukaryotic organelles are based on lipid bilayers that are similar (but not identical) to the cell's outer membrane. Together, the total area of a cell's internal membranes far exceeds that of its plasma membrane.

Like the plasma membrane, organelle membranes function to keep the inside "in" and the outside "out." This partitioning permits different kinds of biochemical reactions to take place in different organelles. Although each organelle performs a specific function in the cell, all of the cell's organelles work together in an integrated fashion to meet the overall needs of the cell. For example, biochemical reactions in a cell's mitochondria transfer energy from fatty acids and pyruvate molecules into an energy-rich molecule called **adenosine triphosphate** (**ATP**). Subsequently, the rest of the cell's organelles use this ATP as the source of the energy they need to operate.

Because most organelles are surrounded by membranes, they are easy to visualize — with magnification. For instance, researchers can use high resolution **electron microscopy** to take a snapshot through a thin cross-section or slice of a cell. In this way, they can see the structural detail and key characteristics of different organelles — such as the long, thin compartments of the endoplasmic reticulum or the compacted chromatin within the nucleus. An electron micrograph therefore provides an excellent blueprint of a cell's inner structures. Other less powerful microscopy techniques coupled with organelle-specific stains have helped researchers see organelle structure more clearly, as well as the distribution of various organelles within cells. However, unlike the rooms in a house, a cell's organelles are not static. Rather, these structures are in constant motion, sometimes moving to a particular place within the cell, sometimes merging with other organelles, and sometimes growing larger or smaller. These dynamic changes in cellular structures can be observed with video microscopic techniques, which provide lower-resolution movies of whole organelles as these structures move within cells.

Why Is the Nucleus So Important?

Of all eukaryotic organelles, the nucleus is perhaps the most critical. In fact, the mere presence of a nucleus is considered one of the defining features of a eukaryotic cell. This structure is so important because it is the site at which the cell's DNA is housed and the process of interpreting it begins.

Recall that DNA contains the information required to build cellular proteins. In eukaryotic cells, the membrane that surrounds the nucleus — commonly called the **nuclear envelope** — partitions this DNA from the cell's protein synthesis machinery, which is located in the cytoplasm. Tiny pores in the nuclear envelope, called **nuclear pores,** then selectively permit certain macromolecules to enter and leave the nucleus — including the RNA molecules that carry information from a cellular DNA to protein manufacturing centers in the cytoplasm. This separation of the DNA from the protein synthesis machinery provides eukaryotic cells with more intricate regulatory control over the production of proteins and their RNA intermediates.

In contrast, the DNA of prokaryotic cells is distributed loosely around the cytoplasm, along with the protein synthesis machinery. This closeness allows prokaryotic cells to rapidly respond to environmental change by quickly altering the types and amount of proteins they manufacture. Note that eukaryotic cells likely evolved from a symbiotic relationship between two prokaryotic cells, whereby one set of prokaryotic DNA eventually became separated by a nuclear envelope and formed a nucleus. Over time, portions of the DNA from the other prokaryote remaining in the cytoplasmic part of the cell may or may not have been incoporated into the new eukaryotic nucleus (Figure 3).

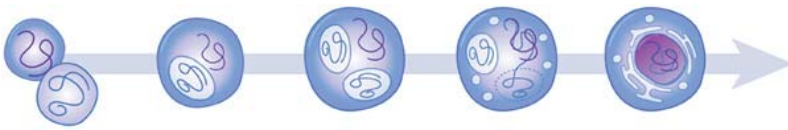

Figure 3: Origin of a eukaryotic cell
A prokaryotic host cell incorporates another prokaryotic cell. Each prokaryote has its own set of DNA molecules (a genome). The genome of the incorporated cell remains separate (curved blue line) from the host cell genome (curved purple line). The incorporated cell may continue to replicate as it exists within the host cell. Over time, during errors of replication or perhaps when the incorporated cell lyses and loses its membrane separation from the host, genetic material becomes separated from the incorporated cell and merges with the host cell genome. Eventually, the host genome becomes a mixture of both genomes, and it ultimately becomes enclosed in an endomembrane, a membrane within the cell that creates a separate compartment. This compartment eventually evolves into a nucleus.

Why Are Mitochondria and Chloroplasts Special?

Besides the nucleus, two other organelles — the mitochondrion and the chloroplast — play an especially important role in eukaryotic cells. These specialized structures are enclosed by double membranes, and they are believed to have originated back when all living things on Earth were single-celled organisms. At that time, some larger eukaryotic cells with flexible membranes "ate" by engulfing molecules and smaller cells — and scientists believe that mitochondria and chloroplasts arose as a result of this process. In particular, researchers think that some of these "eater" eukaryotes engulfed smaller prokaryotes, and a symbiotic relationship subsequently developed. Once kidnapped, the "eaten" prokaryotes continued to generate energy and carry out other necessary cellular functions, and the host eukaryotes came to rely on the contribution of the "eaten" cells. Over many generations, the descendants of the eukaryotes developed mechanisms to further support this system, and concurrently, the descendants of the engulfed prokaryotes lost the ability to survive on their own, evolving into present-day mitochondria and chloroplasts. This proposed origin of mitochondria and chloroplasts is known as the **endosymbiotic hypothesis**.

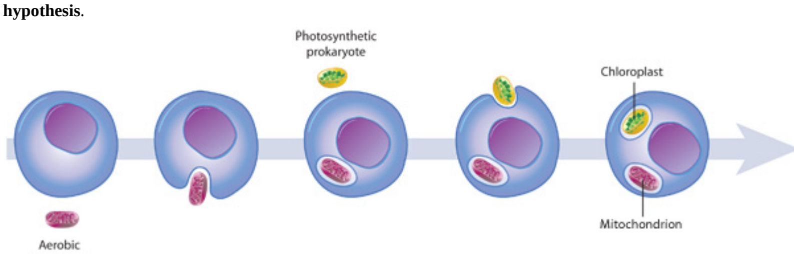

Figure 4: The origin of mitochondria and chloroplasts
Mitochondria and chloroplasts likely evolved from engulfed bacteria that once lived as independent organisms. At some point, a eukaryotic cell engulfed an aerobic bacterium, which then formed an endosymbiotic relationship with the host eukaryote, gradually developing into a mitochondrion. Eukaryotic cells containing mitochondria then engulfed photosynthetic bacteria, which evolved to become specialized chloroplast organelles.

In addition to double membranes, mitochondria and chloroplasts also retain small genomes with some resemblance to those found in modern prokaryotes. This finding provides yet additional evidence that these organelles probably originated as self-sufficient single-celled organisms.

Today, mitochondria are found in fungi, plants, and animals, and they use oxygen to produce energy in the form of ATP molecules, which cells then employ to drive many processes. Scientists believe that mitochondria evolved from **aerobic**, or oxygen-consuming, prokaryotes. In comparison, chloroplasts are found in plant cells and some algae, and they convert solar energy into energy-storing sugars such as glucose. Chloroplasts also produce oxygen, which makes them necessary for all life as we know it. Scientists think chloroplasts evolved from **photosynthetic** prokaryotes similar to modern-day **cyanobacteria** (Figure 4). Today, we classify prokaryotes and eukaryotes based on differences in their cellular contents (Figure 5).

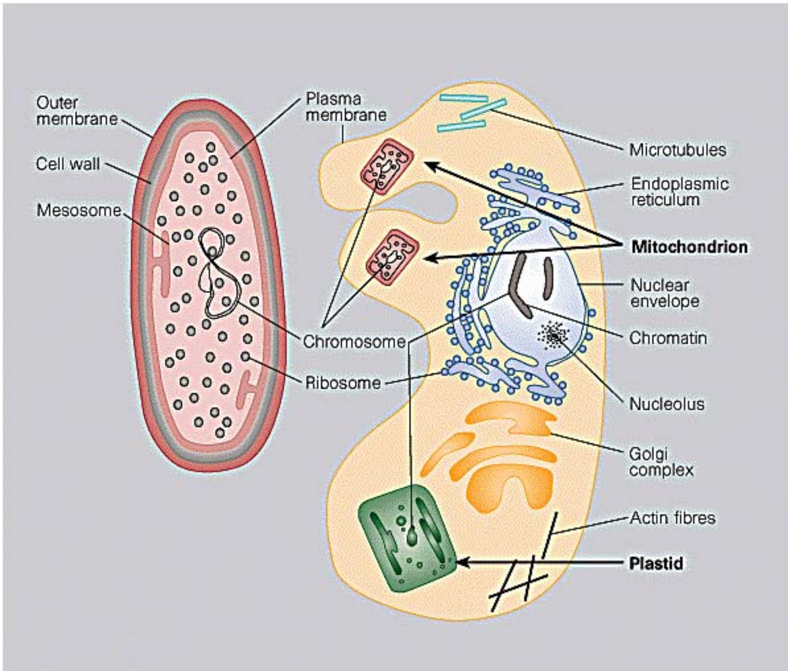

Figure 5: Typical prokaryotic (left) and eukaryotic (right) cells
In prokaryotes, the DNA (chromosome) is in contact with the cellular cytoplasm and is not in a housed membrane-bound nucleus. In eukaryotes, however, the DNA takes the form of compact chromosomes separated from the rest of the cell by a nuclear membrane (also called a nuclear envelope). Eukaryotic cells also contain a variety of structures and organelles not present in prokaryotic cells. Throughout the course of evolution, organelles such as mitochondria and chloroplasts (a form of plastid) may have arisen from engulfed prokaryotes.

How Do Eukaryotic Cells Handle Energy?

Mitochondria — often called the powerhouses of the cell — enable eukaryotes to make more efficient use of food sources than their prokaryotic counterparts. That's because these organelles greatly expand the amount of membrane used for energy-generating electron transport chains. In addition, mitochondria use a process called **oxidative metabolism** to convert food into energy, and oxidative metabolism yields more energy per food molecule than non-oxygen-using, or **anaerobic**, methods. Energywise, cells with mitochondria can therefore afford to be bigger than cells without mitochondria.

Within eukaryotic cells, mitochondria function somewhat like batteries, because they convert energy from one form to another: food nutrients to ATP. Accordingly, cells with high metabolic needs can meet their higher energy demands by increasing the number of mitochondria they contain. For example, muscle cells in people who exercise regularly possess more mitochondria than muscle cells in sedentary people.

Prokaryotes, on the other hand, don't have mitochondria for energy production, so they must rely on their immediate environment to obtain usable energy. Prokaryotes generally use electron transport chains in their plasma membranes to provide much of their energy. The actual energy donors and acceptors for these electron transport chains are quite variable, reflecting the diverse range of habitats where prokaryotes live. (In aerobic prokaryotes, electrons are transferred to oxygen, much as in the mitochondria.) The challenges associated with energy generation limit the size of prokaryotes. As these cells grow larger in volume, their energy needs increase proportionally. However, as they increase in size, their surface area — and thus their ability to both take in nutrients and transport electrons — does not increase to the same degree as their volume. As a result, prokaryotic cells tend to be small so that they can effectively manage the balancing act between energy supply and demand (Figure 6).

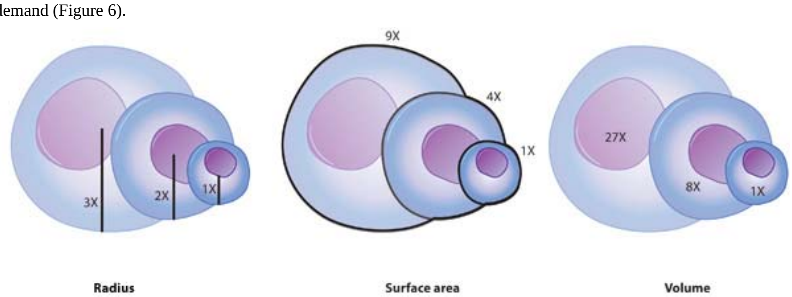

Figure 6: The relationship between the radius, surface area, and volume of a cell

Note that as the radius of a cell increases from 1x to 3x (left), the surface area increases from 1x to 9x, and the volume increases from 1x to 27x.

Conclusion

Organelles serve specific functions within eukaryotes, such as energy production, photosynthesis, and membrane construction. Most are membrane-bound structures that are the sites of specific types of biochemical reactions. The nucleus is particularly important among eukaryotic organelles because it is the location of a cell's DNA. Two other critical organelles are mitochondria and chloroplasts, which play important roles in energy conversion and are thought to have their evolutionary origins as simple single-celled organisms.

Unit 1

- Cells Are the Basic Units of Living Organisms
- Eukaryotic Cells Possess a Nucleus and Membrane-Bound Organelles
  - What Defines an Organelle?
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  - Why Are Mitochondria and Chloroplasts Special?
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  - Conclusion
- Cell Function Depends on the Continual Uptake and Conversion of Energy
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- Test Your Knowledge

- View Paginated