Introduction to eukaryotic cells

By definition, *eukaryotic cells* are cells that contain a membrane-bound nucleus, a structural feature that is not present in bacterial or archaeal cells. In addition to the nucleus, *eukaryotic cells* are characterized by numerous membrane-bound *organelles* such as the endoplasmic reticulum, Golgi apparatus, chloroplasts, mitochondria, and others.

In previous sections, we began to consider the Design Challenge of making cells larger than a small bacterium—more precisely, growing cells to sizes at which, in the eyes of natural selection, relying on diffusion of substances for transport through a highly viscous cytosol comes with inherent functional trade-offs that offset most selective benefits of getting larger. In the lectures and readings on bacterial cell structure, we discovered some morphological features of large bacteria that allow them to effectively overcome diffusion-limited size barriers (e.g., filling the cytoplasm with a large storage vacuole maintains a small volume for metabolic activity that remains compatible with diffusion-driven transport).

As we transition our focus to eukaryotic cells, we want you to approach the study by constantly returning to the Design Challenge. We will cover a large number of subcellular structures that are unique to eukaryotes, and you will certainly be expected to know the names of these structures or organelles, to associate them with one or more "functions", and to identify them on a canonical cartoon representation of a eukaryotic cell. This memorization exercise is necessary but not sufficient. We will also ask you to start thinking a bit deeper about some of the functional and evolutionary costs and benefits (trade-offs) of both evolving eukaryotic cells and various eukaryotic organelles, as well as how a eukaryotic cell might coordinate the functions of different organelles.
Your instructors will, of course, propose some functional hypotheses for you to consider that address these broader points. Our hypotheses may sometimes come in the form of statements like, "Thing A exists because of rationale B." To be completely honest, however, in many cases, we don't actually know all of the selective pressures that led to the creation or maintenance of certain cellular structures, and the likelihood that one explanation will fit all cases is slim in biology. The causal linkage/relationship implied by the use of terms like "because" should be treated as good hypotheses rather than objective, concrete, undisputed, factual knowledge. We want you to understand these hypotheses and to be able to discuss the ideas presented in class, but we also want you to indulge your own curiosity and to begin thinking critically about these ideas yourself. Try using the Design Challenge rubric to explore some of your ideas. In the following, we will try to seed questions to encourage this activity.

Figure 1. These figures show the major organelles and other cell components of (a) a typical animal cell and (b) a typical eukaryotic plant cell. The plant cell has a cell wall, chloroplasts, plastids, and a central vacuole—structures not found in animal cells. Plant cells do not have lysosomes or centrosomes.

The plasma membrane

Like bacteria and archaea, eukaryotic cells have a plasma membrane, a phospholipid bilayer with embedded proteins that separates the internal contents of the cell from its surrounding environment. The plasma membrane controls the passage of organic molecules, ions, water, and oxygen into and out of the cell. Wastes (such as carbon dioxide and ammonia) also leave the cell by passing through the plasma membrane, usually with some help of protein transporters.
Figure 2. The eukaryotic plasma membrane is a phospholipid bilayer with proteins and cholesterol embedded in it.

As discussed in the context of bacterial cell membranes, the plasma membranes of eukaryotic cells may also adopt unique conformations. For instance, the plasma membrane of cells that, in multicellular organisms, specialize in absorption are often folded into fingerlike projections called microvilli (singular = microvillus); (see figure below). The "folding" of the membrane into microvilli effectively increases the surface area for absorption while minimally impacting the cytosolic volume. Such cells can be found lining the small intestine, the organ that absorbs nutrients from digested food.

An aside: People with celiac disease have an immune response to gluten, a protein found in wheat, barley, and rye. The immune response damages microvilli. As a consequence, afflicted individuals have an impaired ability to absorb nutrients. This can lead to malnutrition, cramping, and diarrhea.

Figure 3. Microvilli, shown here as they appear on cells lining the small intestine, increase the surface area available for absorption. These microvilli are only found on the area of the plasma membrane that faces the cavity from which substances will be absorbed. Credit: "micrograph", modification of work by Louisa Howard

The cytoplasm

The cytoplasm refers to the entire region of a cell between the plasma membrane and the nuclear envelope. It is composed of organelles suspended in the gel-like cytosol, the cytoskeleton, and various chemicals (see figure below). Even though the cytoplasm consists of 70 to 80 percent water, it nevertheless has a semisolid consistency. It is crowded in there. Proteins, simple sugars, polysaccharides, amino acids, nucleic acids, fatty acids, ions and many other water-soluble molecules are all competing for space and water.
The nucleus

Typically, the nucleus is the most prominent organelle in a cell (see figure below) when viewed through a microscope. The *nucleus* (plural = nuclei) houses the cell’s DNA. Let’s look at it in more detail.

![Diagram of the nucleus](https://bio.libretexts.org/Courses/University_of_California_Davis/BIS_2A%3A_Introductory_Biology_(Easlon)/Readings/02.3%3A

**Figure 4.** The nucleus stores chromatin (DNA plus proteins) in a gel-like substance called the nucleoplasm. The nucleolus is a condensed region of chromatin where ribosome synthesis occurs. The boundary of the nucleus is called the nuclear envelope. It consists of two phospholipid bilayers: an outer membrane and an inner membrane. The nuclear membrane is continuous with the endoplasmic reticulum. Nuclear pores allow substances to enter and exit the nucleus.

The nuclear envelope

The *nuclear envelope*, a structure that constitutes the outermost boundary of the nucleus, is a double-membrane—both the inner and outer membranes of the nuclear envelope are phospholipid bilayers. The nuclear envelope is also punctuated with protein-based pores that control the passage of ions, molecules, and RNA between the nucleoplasm and cytoplasm. The *nucleoplasm* is the semisolid fluid inside the nucleus where we find the chromatin and the nucleolus, a condensed region of chromatin where ribosome synthesis occurs.

Chromatin and chromosomes

To understand chromatin, it is helpful to first consider chromosomes. *Chromosomes* are structures within the nucleus that are made up of DNA, the hereditary material. You may remember that in bacteria and archaea, DNA is typically organized into one or more circular chromosome(s). In eukaryotes, chromosomes are linear structures. Every eukaryotic species has a specific number of chromosomes in the nuclei of its cells. In humans, for example, the chromosome number is 23, while in fruit flies, it is 4.

Chromosomes are only clearly visible and distinguishable from one another by visible optical microscopy when the cell is preparing to divide and the DNA is tightly packed by proteins into easily distinguishable shapes. When the cell is in the growth and maintenance phases of its life cycle, numerous proteins are still associated with the nucleic acids, but
the DNA strands more closely resemble an unwound, jumbled bunch of threads. The term *chromatin* is used to describe chromosomes (the protein-DNA complexes) when they are both condensed and decondensed.

![Image of chromatin](https://bio.libretexts.org/Courses/University_of_California_Davis/BIS_2A%3A_Introductory_Biology_(Easlon)/Readings/02.3%3A_Eukaryotic_Cell%3A_Structure_and_Function)

**Figure 5.** (a) *This image shows various levels of the organization of chromatin (DNA and protein)*. (b) *This image shows paired chromosomes*. Credit (b): modification of work by NIH; scale-bar data from Matt Russell

## The nucleolus

Some chromosomes have sections of DNA that encode ribosomal RNA. A darkly staining area within the nucleus called the *nucleolus* (plural = nucleoli) aggregates the ribosomal RNA with associated proteins to assemble the ribosomal subunits that are then transported out to the cytoplasm through the pores in the nuclear envelope.

Note: possible discussion

Discuss amongst yourselves. Use the Design Challenge rubric to consider the nucleus in more detail. What "problems" does an organelle like the nucleus solve? What are some of the qualities of a nucleus that may be responsible for ensuring its evolutionary success? What are some of the trade-offs of evolving and maintaining a nucleus? (Every benefit has some cost; can you list both?) Remember, there may be some well-established hypotheses (and it is good to mention these), but the point of the exercise here is for you to think critically and to critically discuss these ideas using your collective "smarts".

## Ribosomes

*Ribosomes* are the cellular structures responsible for protein synthesis. When viewed through an electron microscope, ribosomes appear either as clusters (polyribosomes) or single, tiny dots that float freely in the cytoplasm. They may be attached to the cytoplasmic side of the plasma membrane or the cytoplasmic side of the endoplasmic reticulum and the...
outer membrane of the nuclear envelope (cartoon of cell above).

Electron microscopy has shown us that ribosomes, which are large complexes of protein and RNA, consist of two subunits, aptly called large and small (figure below). Ribosomes receive their "instructions" for protein synthesis from the nucleus, where the DNA is transcribed into messenger RNA (mRNA). The mRNA travels to the ribosomes, which translate the code provided by the sequence of the nitrogenous bases in the mRNA into a specific order of amino acids in a protein. This is covered in greater detail in the section covering the process of translation.

![Ribosome Diagram](https://bio.libretexts.org/Courses/University_of_California_Davis/BIS_2A%3A_Introductory_Biology_(Easlon)/Readings/02.3%3A)

**Figure 6.** *Ribosomes are made up of a large subunit (top) and a small subunit (bottom). During protein synthesis, ribosomes assemble amino acids into proteins.*

## Mitochondria

*Mitochondria* (singular = mitochondrion) are often called the “powerhouses” or “energy factories” of a cell because they are the primary site of metabolic respiration in eukaryotes. Depending on the species and the type of mitochondria found in those cells, the respiratory pathways may be anaerobic or aerobic. By definition, when respiration is aerobic, the terminal electron is oxygen; when respiration is anaerobic, a compound other than oxygen functions as the terminal electron acceptor. In either case, the result of these respiratory processes is the production of ATP via oxidative phosphorylation, hence the use of terms "powerhouse" and/or "energy factory" to describe this organelle. Nearly all mitochondria also possess a small genome that encodes genes whose functions are typically restricted to the mitochondrion.

In some cases, the number of mitochondria per cell is tunable, depending, typically, on energy demand. It is for instance possible muscle cells that are used—that by extension have a higher demand for ATP—may often be found to have a significantly higher number of mitochondria than cells that do not have a high energy load.

The structure of the mitochondria can vary significantly depending on the organism and the state of the cell cycle which one is observing. The typical textbook image, however, depicts mitochondria as oval-shaped organelles with a double inner and outer membrane (see figure below); learn to recognize this generic representation. Both the inner and
outer membranes are phospholipid bilayers embedded with proteins that mediate transport across them and catalyze various other biochemical reactions. The inner membrane layer has folds called cristae that increase the surface area into which respiratory chain proteins can be embedded. The region within the cristae is called the mitochondrial matrix and contains—among other things—enzymes of the TCA cycle. During respiration, protons are pumped by respiratory chain complexes from the matrix into a region known as the intermembrane space (between the inner and outer membranes).

**Figure 7.** This electron micrograph shows a mitochondrion as viewed with a transmission electron microscope. This organelle has an outer membrane and an inner membrane. The inner membrane contains folds, called cristae, which increase its surface area. The space between the two membranes is called the intermembrane space, and the space inside the inner membrane is called the mitochondrial matrix. ATP synthesis takes place on the inner membrane. Credit: modification of work by Matthew Britton; scale-bar data from Matt Russell

Note: possible discussion

Discuss: Processes like glycolysis, lipid biosynthesis, and nucleotide biosynthesis all have compounds that feed into the TCA cycle—some of which occurs in the mitochondria. What are some of the functional challenges associated with coordinating processes that have a common set of molecules if the enzymes are sequestered into different cellular compartments?

**Peroxisomes**

Peroxisomes are small, round organelles enclosed by single membranes. These organelles carry out redox reactions that oxidize and break down fatty acids and amino acids. They also help to detoxify many toxins that may enter the body. Many of these redox reactions release hydrogen peroxide, H$_2$O$_2$, which would be damaging to cells; however, when these reactions are confined to peroxisomes, enzymes safely break down the H$_2$O$_2$ into oxygen and water. For example, alcohol is detoxified by peroxisomes in liver cells. Glyoxysomes, which are specialized peroxisomes in plants, are responsible for converting stored fats into sugars.

**Vesicles and vacuoles**

Vesicles and vacuoles are membrane-bound sacs that function in storage and transport. Other than the fact that vacuoles are somewhat larger than vesicles, there is a very subtle distinction between them: the membranes of vesicles can fuse with either the plasma membrane or other membrane systems within the cell. Additionally, some agents such as enzymes
within plant vacuoles break down macromolecules. The membrane of a vacuole does not fuse with the membranes of other cellular components.

**Animal cells versus plant cells**

At this point, you know that each eukaryotic cell has a plasma membrane, cytoplasm, a nucleus, ribosomes, mitochondria, peroxisomes, and in some, vacuoles. There are some striking differences between animal and plant cells worth noting. Here is a brief list of differences that we want you to be familiar with and a slightly expanded description below:

1. While all eukaryotic cells use microtubule and motor protein the based mechanisms to segregate chromosomes during cell division, the structures used to organize these microtubules differ in plants versus animal and yeast cells. Animal and yeast cells have microtubule organizing centers (MTOCs). These structures are composed of structures called centrioles that are composed largely of α-tubulin, β-tubulin, and other proteins. Two centrioles organize into a structure called a centrosome. By contrast, in plants, while microtubules also organize into discrete bundles, there are no conspicuous structures similar to the MTOCs seen in animal and yeast cells. Rather, depending on the organism, it appears that there can be several places where these bundles of microtubules can nucleate from so called acentriolar (without centriole) microtubule organizing centers. A third type of tubulin, γ-tubulin, appears to be implicated, but our knowledge of the precise mechanisms used by plants to organize microtubule spindles is still spotty.

2. Animal cells typically have organelles called lysosomes responsible for degradation of biomolecules. Some plant cells contain functionally similar degradative organelles, but there is a debate as to how they should be named. Some plant biologists call these organelles lysosomes while others lump them into the general category of plastids and do not give them a specific name.

3. Plant cells have a cell wall, chloroplasts and other specialized plastids, and a large central vacuole, whereas animal cells do not.

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**The centrosome**

The *centrosome* is a microtubule-organizing center found near the nuclei of animal cells. It contains a pair of centrioles, two structures that lie perpendicular to each other (see figure below). Each centriole is a cylinder of nine triplets of microtubules.

![Centrosome Diagram](https://bio.libretexts.org/Courses/University_of_California_Davis/BIS_2A%3A_Introductory_Biology_(Easlon)/Readings/02.3%3A)
The centrosome consists of two centrioles that lie at right angles to each other. Each centriole is a cylinder made up of nine triplets of microtubules. Nontubulin proteins (indicated by the green lines) hold the microtubule triplets together.

The centrosome (the organelle where all microtubules originate in animal and yeast) replicates itself before a cell divides, and the centrioles appear to have some role in pulling the duplicated chromosomes to opposite ends of the dividing cell. However, the exact function of the centrioles in cell division remains unclear, as cells that have had their centrosome removed can still divide, and plant cells, which lack centrosomes, are capable of cell division.

**Lysosomes**

Animal cells have another set of organelles not found in plant cells: lysosomes. Colloquially, the lysosomes are sometimes called the cell’s “garbage disposal”. Enzymes within the lysosomes aid the breakdown of proteins, polysaccharides, lipids, nucleic acids, and even "worn-out" organelles. These enzymes are active at a much lower pH than that of the cytoplasm. Therefore, the pH within lysosomes is more acidic than the pH of the cytoplasm. In plant cells, many of the same digestive processes take place in vacuoles.

**The cell wall**

If you examine the diagram above depicting plant and animal cells, you will see in the diagram of a plant cell a structure external to the plasma membrane called the cell wall. The cell wall is a rigid covering that protects the cell, provides structural support, and gives shape to the cell. Fungal and protistan cells also have cell walls. While the chief component of bacterial cell walls is peptidoglycan, the major organic molecule in the plant cell wall is cellulose (see structure below), a polysaccharide made up of glucose subunits.

**Figure 9.** Cellulose is a long chain of β-glucose molecules connected by a 1-4 linkage. The dashed lines at each end of the figure indicate a series of many more glucose units. The size of the page makes it impossible to portray an entire cellulose molecule.

**Chloroplasts**

Chloroplasts are plant cell organelles that carry out photosynthesis. Like the mitochondria, chloroplasts have their own DNA and ribosomes, but chloroplasts have an entirely different function.

Like mitochondria, chloroplasts have outer and inner membranes, but within the space enclosed by a chloroplast's inner membrane is a set of interconnected and stacked fluid-filled membrane sacs called thylakoids (figure below). Each stack of thylakoids is called a granum (plural = grana). The fluid enclosed by the inner membrane that surrounds the grana is called the stroma.
Figure 10. The chloroplast has an outer membrane, an inner membrane, and membrane structures called thylakoids that are stacked into grana. The space inside the thylakoid membranes is called the thylakoid space. The light harvesting reactions take place in the thylakoid membranes, and the synthesis of sugar takes place in the fluid inside the inner membrane, which is called the stroma. Chloroplasts also have their own genome, which is contained on a single circular chromosome.

The chloroplasts contain a green pigment called chlorophyll, which captures the light energy that drives the reactions of photosynthesis. Like plant cells, photosynthetic protists also have chloroplasts. Some bacteria perform photosynthesis, but their chlorophyll is not relegated to an organelle.

Evolution connection: Endosymbiosis

We have mentioned that both mitochondria and chloroplasts contain DNA and ribosomes. Have you wondered why? Strong evidence points to endosymbiosis as the explanation.

Symbiosis is a relationship in which organisms from two separate species depend on each other for their survival. Endosymbiosis (endo- = "within") is a mutually beneficial relationship in which one organism lives inside the other. Endosymbiotic relationships abound in nature. For instance, some microbes that live in our digestive tracks produce vitamin K. The relationship between these microbes and us (their hosts) is said to be mutually beneficial or symbiotic. The relationship is beneficial for us because we are unable to synthesize vitamin K; the microbes do it for us instead. The relationship is also beneficial for the microbes because they receive abundant food from the environment of the large intestine, and they are protected both from other organisms and from drying out.

Scientists have long noticed that bacteria, mitochondria, and chloroplasts are similar in size. We also know that bacteria have DNA and ribosomes, just as mitochondria and chloroplasts do. Scientists believe that host cells and bacteria formed an endosymbiotic relationship when the host cells ingested both aerobic and autotrophic bacteria (cyanobacteria) but did not destroy them. Through many millions of years of evolution, these ingested bacteria became more specialized in their functions, with the aerobic bacteria becoming mitochondria and the autotrophic bacteria becoming chloroplasts. There will be more on this later in the reading.
The central vacuole

Previously, we mentioned vacuoles as essential components of plant cells. If you look at the cartoon figure of the plant cell, you will see that it depicts a large central vacuole that occupies most of the area of the cell. The central vacuole plays a key role in regulating the cell’s concentration of water in changing environmental conditions.

Silly vacuole factoid: Have you ever noticed that if you forget to water a plant for a few days, it wilts? That’s because as the water concentration in the soil becomes lower than the water concentration in the plant, water moves out of the central vacuoles and cytoplasm. As the central vacuole shrinks, it leaves the cell wall unsupported. This loss of support to the cell walls of plant cells results in the wilted appearance of the plant.

The central vacuole also supports the expansion of the cell. When the central vacuole holds more water, the cell gets larger without having to invest a lot of energy in synthesizing new cytoplasm.