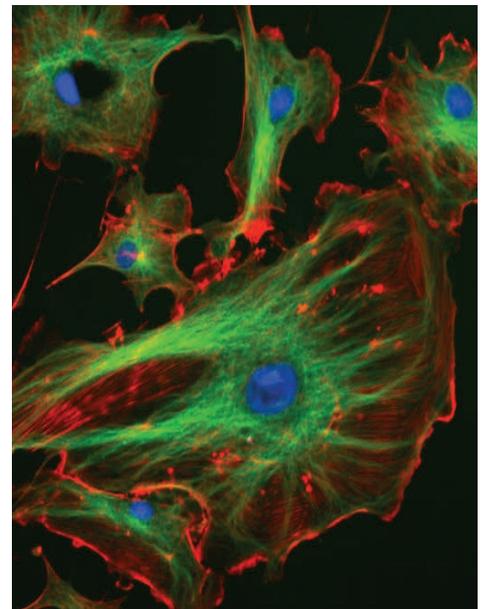


CHAPTER 3: THE CYTOSKELETON AND MOTOR PROTEINS

Inside their membranes, cells are filled with a watery fluid called **cytosol**. The word “cyto” means “cell,” and the ending “-sol” is short for “solution.” The term **cytoplasm** is also used to describe the watery insides of a cell, but this term includes not only the fluid but also small things that are floating around in it. It can seem like these words mean the same thing because science writers use them almost interchangeably. To be fair, in many cases it doesn’t really matter which word the writer chooses because either word will fit the meaning of the sentence. A helpful analogy might be to think of a can of soup. If the can is the membrane, the soup is the cytoplasm. If the soup is chicken noodle, it has noodles and bits of chicken floating in broth. The word “cytosol” would correspond to the broth. The words “soup” and “broth” are very similar, but we can use the more specific word “broth” when we want to talk about only the liquid element of the soup, not the things floating in it. In many conversations, the word “soup” is good enough and we don’t have to be any more specific than that.

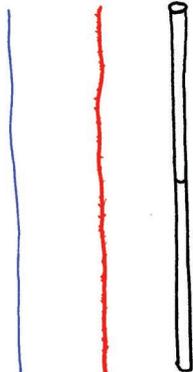
In 1903, a Russian scientist proposed that cells must have some kind of network inside that helps them keep their shape. He reasoned that if cells were nothing but a bag of liquid, they would be too easily flattened. The cells he saw in his microscope were anything but flat. This proposed network of fibers was nothing but a theory until the 1970s, when scientists discovered a way to detect fibers too thin to be seen under a microscope. Trying to see these filaments in the cytosol is like trying to see fishing line underwater. Both are transparent, and the fishing line is very thin. (That’s the whole idea—the fish can’t see it!)

The breakthrough came in the 1970s. Someone discovered a natural molecule (antibody) that would stick to these invisible fibers. This natural molecule could be stained with fluorescent dyes that glowed green or red. If you put these stained molecules into a cell, they would stick to the fibers and make them show up as brightly colored lines. The images produced in these experiments were stunning. They showed organized networks of filaments, like a three-dimensional system of roads and highways. It was obvious that this network of fibers acted as a structural support, so it was named the **cytoskeleton**.

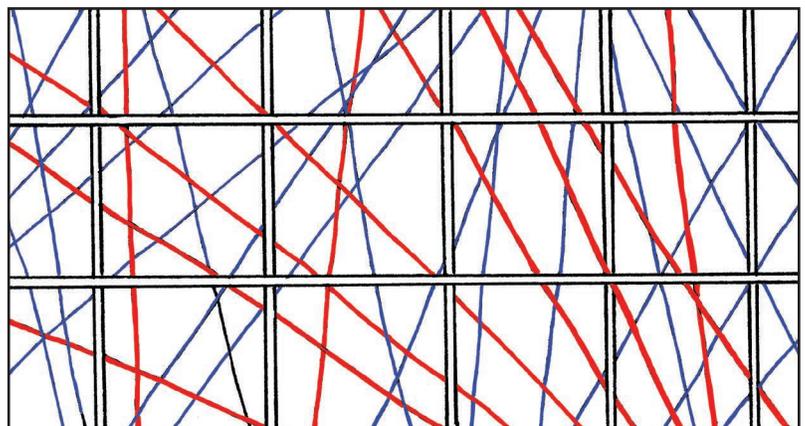


With further research, scientists discovered that the cytoskeleton not only helps the cell to maintain its shape, but also functions as a transportation system. It really does act like a system of roads and highways. The roads come in three sizes: small, medium and large. The scientists who discovered them gave them these names: **microfilaments, intermediate filaments and microtubules**. If we were to make a model of a cytoskeleton we might use thread, yarn, and drinking straws to represent these fibers.

THREAD YARN STRAWS



You could create a cytoskeleton model in your room by stretching thread, yarn and straws from wall to wall!

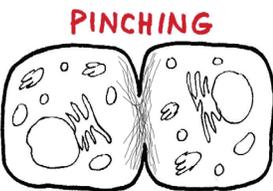
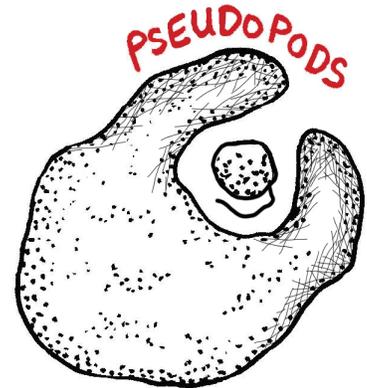


The smallest ones, the **microfilaments** (the thread in our model) are made of protein molecules called **actin**, so the filaments are also known as **actin filaments**.



The balls represent little units of actin protein. More about protein later in the book.

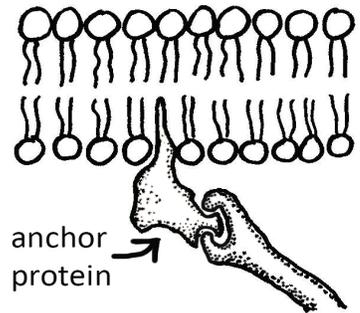
The microfilaments are very important to the overall shape of the cell, and can also help the cell to change its shape. If a cell wants to move, it quickly builds a whole bunch of new microfilaments in that direction. The cell can build these at the rate of thousands per second. As the new microfilaments are built, they push the flexible membrane outward. Cytoplasm flows along with the microfilaments. Together they create what is called a **pseudopod**, or “false foot.” (Can you see the tiny microfilament lines in the pseudopods in this diagram?) We have white blood cells in our bodies that form pseudopods in order to surround and capture bacteria and viruses. Single-celled organisms like the ameba (old spelling: amoeba) also use pseudopods to move through their environment. In fact, this type of movement is often called “ameboid motion.”



Microfilaments are also very important when it is time for the cell to reproduce by splitting itself in half. The microfilaments cause the cell to “pinch” in the middle, in preparation for the splitting process.

In some types of cells, such as muscle cells, we find actin filaments being used as a track along which another protein, **myosin**, can travel. The interaction between actin and myosin is what allows you to move your muscles. Most anatomy courses cover this topic quite thoroughly, so we’ll just give it a brief mention in the last chapter when we look at various types of cells.

The medium-sized **intermediate filaments** (the yarn in our model) are especially abundant in nerve cells, skin cells, and muscle cells. They form a stretchy lattice inside the cell that help to give it strength. In skin cells, an intermediate filament called **keratin** forms a very strong, stretchy network that gives skin its flexibility and durability. It adheres to several types of anchor proteins in the membrane. One type allows skin cells to make strong connections to each other.

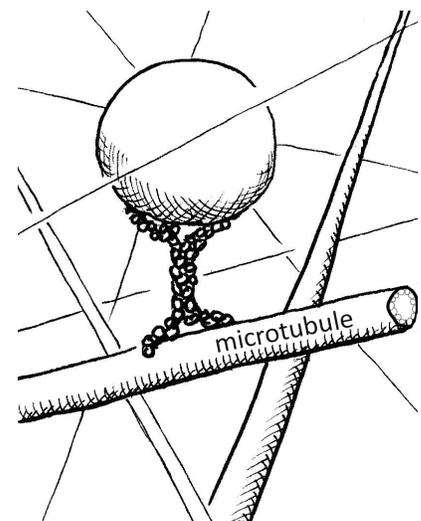


The shapes of the anchor proteins match the ends of the filaments a bit like like jigsaw puzzle pieces that fit together.

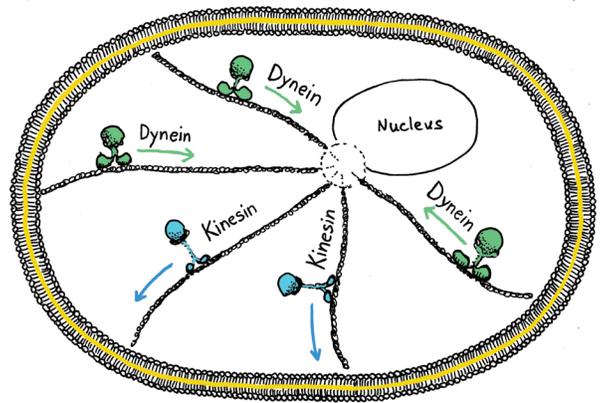
What would happen if something went wrong with the manufacturing process and the cell accidentally made these protein anchors the wrong shape? The intermediate filaments would not stay anchored. When this happens in muscle cells, it can cause a condition called muscular dystrophy. A person with this condition has very weak muscles. When intermediate filaments (keratins) in skin cells are the wrong shape, it causes life-threatening skin diseases.

The largest filaments, the **microtubules** (the drinking straws in our model), really do look like tubes. These tubes are the “highways” that the cell uses to move things about. What does a cell need to move?

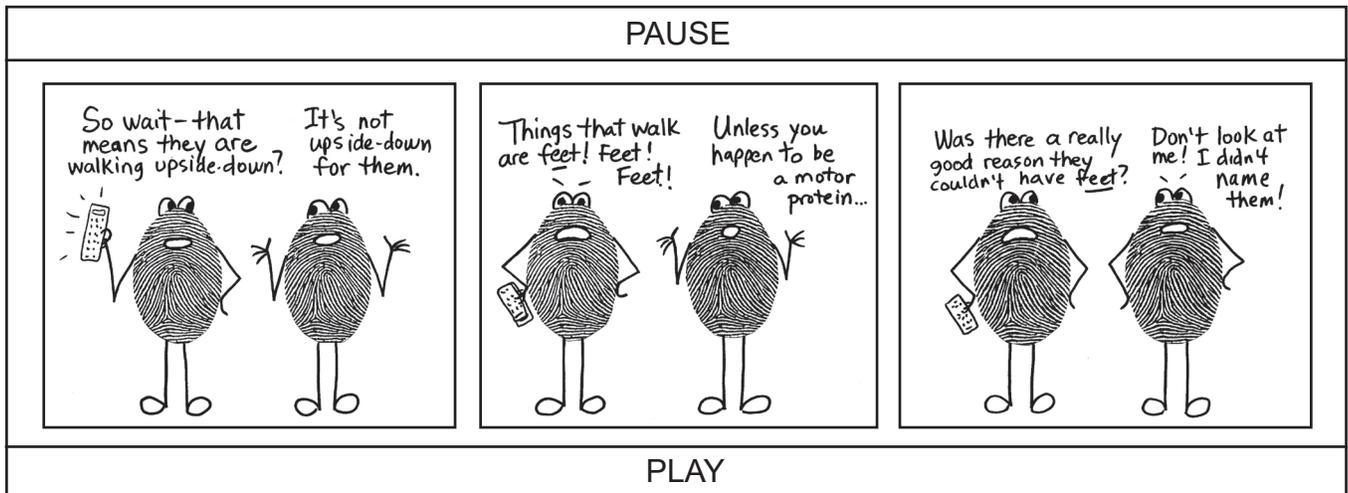
Some of the cell’s organelles act like little factories and make proteins, fats and enzymes for their own use or to ship out to other cells. These products are then “packaged” into vesicles made of phospholipid membrane. The packages can’t move on their own, so something has to take them to where they need to go. When it was discovered how this transport happens, scientists could hardly believe their eyes—they saw little proteins with “feet” that were “walking” along the microtubule roads! These **motor proteins** move like tightrope walkers at a circus, putting one foot in front of the other along the narrow rope. They carry their cargo as if it was a huge sack resting on their shoulders. How the motor proteins know where to go is still being studied.



There are several types of motor proteins. The ones that are most abundant (and therefore the most studied) are called **kinesin** (*kin-EE-sun*) and **dynein** (*DIE-nin*). As a general rule, they seem to “walk” in only one direction. Kinesin carries things away from the central nucleus and towards the outer membrane. Dynein goes the opposite way, carrying things from the outside towards the center. When they get to the end of the line and have fulfilled their mission, they often drop off the tubule and eventually float back towards their starting point. Then they receive new instructions and are off on another mission. They probably won’t attach to the same tubule they used for the previous mission. Their missions can be as short as a few seconds or as long as a few minutes. If a kinesin and dynein run into each other, one of them will probably fall off, or dynein might side step long enough to let kinesin pass.



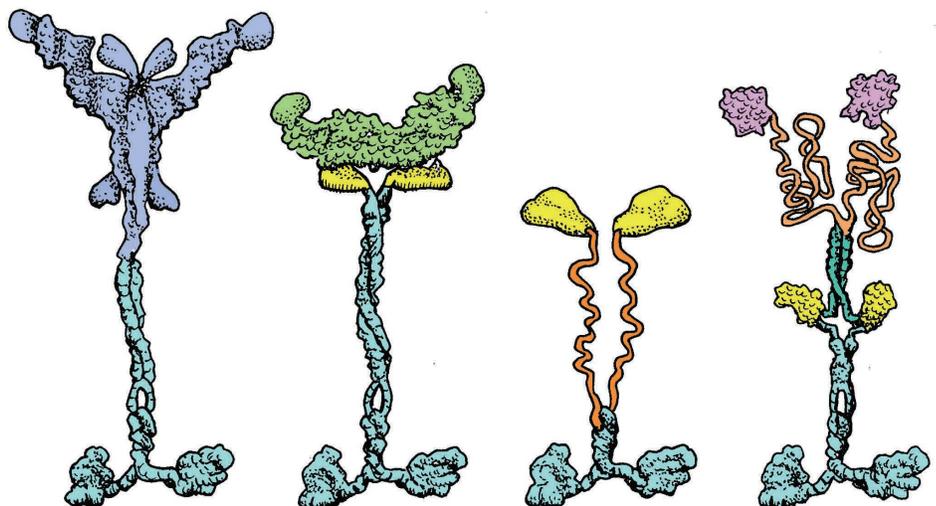
Now, here comes the tricky part. The things that look like feet on a motor protein are actually called **heads**. And the things that look like its hands (holding the load) are actually called its **tails**.



Yes, it is unfortunate. Sorry. But let’s learn a little more about these heads and tails.

The shape and structure of motor protein heads is pretty standard because they all have to walk along the same tubule roads. Their tails can be quite different, though, because a particular shape is needed to connect to a particular type of cargo. The part of a motor protein that connects to the cargo is called the **binding site**. (This term is also used for the place on each head that touches the microtubule.) So far, scientists have identified about 40 types of cargo binding sites. This picture shows four different kinesins. The one on the left is considered “standard” (the most common kinesin) and the others are variations.

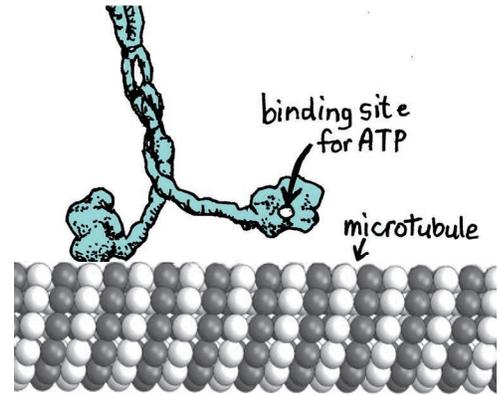
Make sure you watch the recommended videos listed at the end of this chapter so you can see these guys in action!



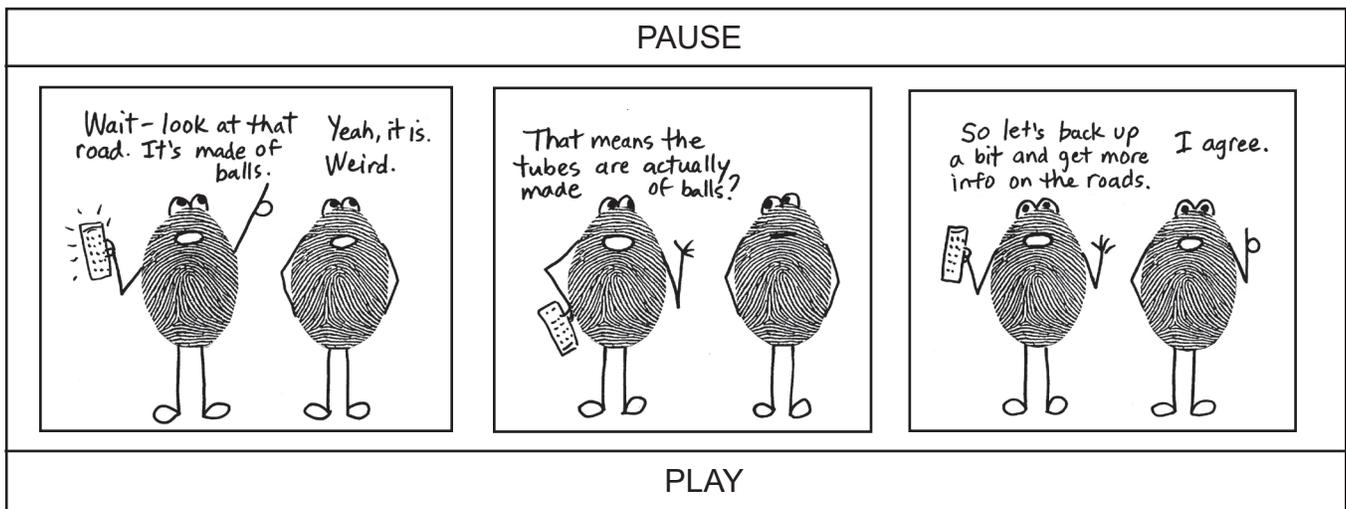
Notice that the heads (feet) all look the same. The tails (top) are specialized for different cargo. They don't have any natural color, but scientists often add color to diagrams.

With each step a motor protein takes, it will use a tiny energy molecule called ATP, which we will study in the next chapter. These steps occur very quickly, much faster than you can walk. One researcher saw a motor protein talking 100 steps per second. This would be like you running as fast as a car on a highway! They can also carry loads much larger than themselves, the equivalent of you towing a house. For exceptionally large cargo, several motor proteins can work together.

When a motor protein wears out (after only a day of action) it will be taken apart and its parts recycled, as if it was a used car. There are tiny factories inside the cell that are constantly using the atoms and molecules from the old motor proteins (and from other recycled cell parts) to make new ones.

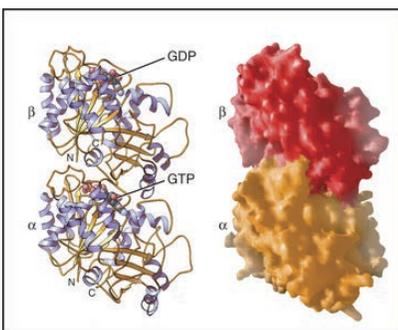


How important are these motor proteins to the life of a cell? Well, just imagine what would happen to your town or city if many of the cars and trucks stopped working. Mail might not get delivered, food would not be shipped to grocery stores, hospital workers might be stuck at home, and construction materials might never arrive at construction sites. Everyone in the town or city would be eventually be affected by the failure of the transportation system. When things go wrong with a cell's transport system, the result is often a very serious disease.



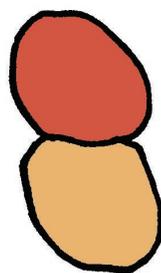
Microtubules are made of tiny individual units of protein called **tubulin**. (As mentioned previously, we'll learn exactly what protein is in a later chapter.) There are two types of tubulin: *alpha* tubulin and *beta* tubulin. You will see the words "alpha" and "beta" used a lot in biology. They are Greek words for the letters A and B.

One alpha and one beta tubulin snap together to make a pair that stays together. There is a special word for a pair of molecules, a word that is easy to pronounce and to spell: **dimer**. ("Di" is Greek for "two.") The cytosol of the cell is FULL of these tubulin dimers. They are simply everywhere!

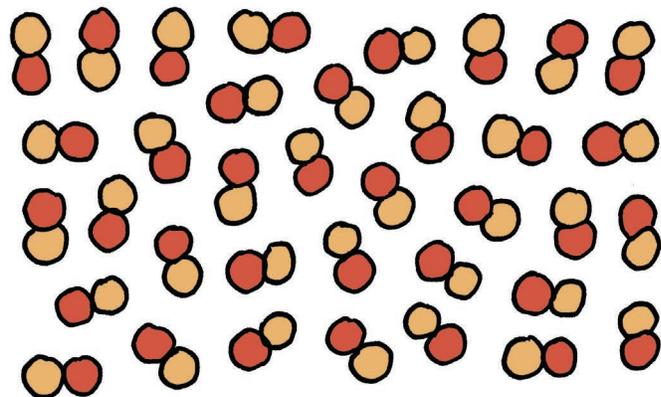


Most accurate drawing of tubulin.

Slightly simplified way to draw it.



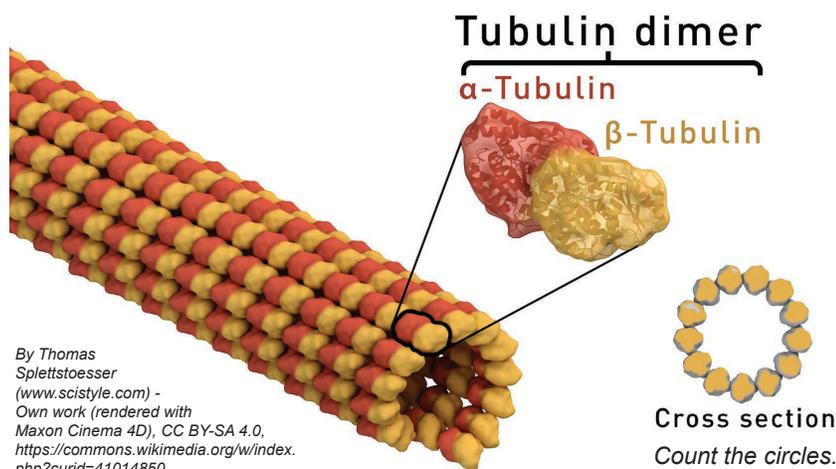
Simple enough for us to draw!



When two dimers bump into each other, they can stick together if a tiny molecule called GTP is present. GTP is similar to ATP, the energy molecule that motor proteins use. GTP fits into a little pocket in the tubulin molecule. When it sticks, it changes the shape of the dimer just slightly, making it a little more straight. Once it has been

straightened, the tubulin dimer will be able to stick to other dimers. When there are many straightened dimers, they will form long lines, then the lines will stick together to form sheets. The sheets will curl up to form tubes. (Video animations can show you this process in action. Be sure to check out the videos on the Cells playlist, or search for some on your own.)

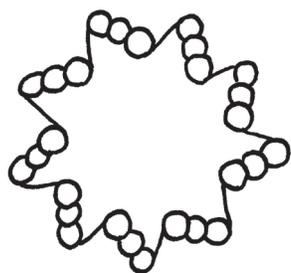
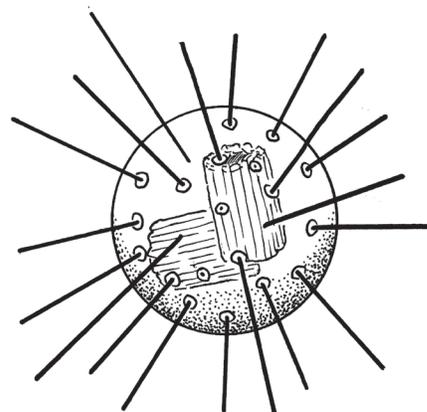
Often there are “helper proteins” in the area, too, that will come alongside the forming tubes and help to add more dimers to the growing (“positive”) end.



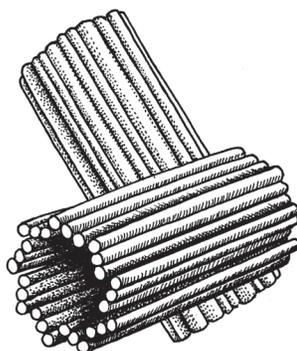
By Thomas Spletstoesser (www.scistyle.com) - Own work (rendered with Maxon Cinema 4D), CC BY-SA 4.0, <https://commons.wikimedia.org/w/index.php?curid=41014850>

If we look at the end of a tubule, we can count exactly how many dimers it takes to form the tube: 13. Isn't that an odd number to find in something biological? Although it is one of the Fibonacci numbers (1, 2, 3, 5, 8, 13, 21, 34, 55, etc.) it only shows up occasionally in a flowering plant.

Microtubules are not scattered randomly around the cell. Like a well-designed city, the cell's roadways are very organized. There is a central “hub” for the microtubules, like a railway station from which all the train tracks branch out. This central station is called the **centrosome**. (“Som” or “soma” is Greek for “body,” but it is often used in the same way that we use the word “thing.”) The centrosome is also called the **microtubule organizing center** of the cell. It is made of two **centrioles** surrounded by a blob of protein gel. The little places where the microtubules are attached are cone-shaped structures (made of another type of tubulin) that acts like a foundation platform on which a microtubule can start to grow. The attached ends of a tubule are called the “negative” ends. Dynein walks towards them.



Cross section showing the “end view” of the centriole



If we take a close-up look at those barrel-shaped centrioles inside the centrosome, we can see that they are made of microtubules arranged in a very precise pattern. Three microtubules get bundled together in a straight line. Then nine of these flat bundles are arranged into a circle. Some thin protein fibers hold them in place.

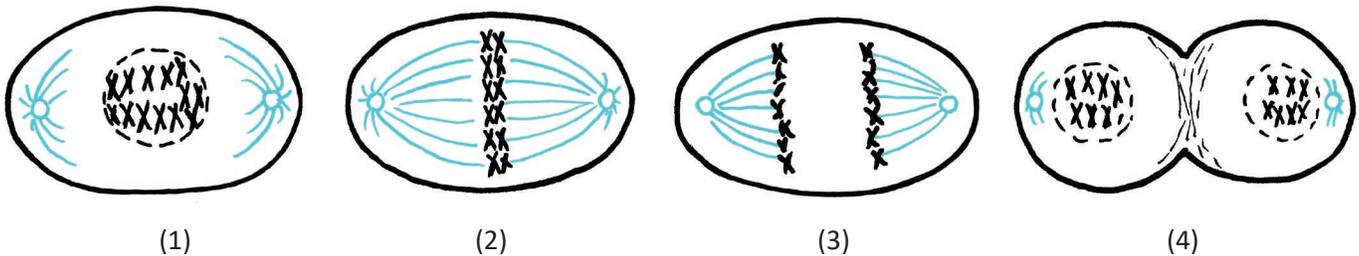
Notice that the centrioles are perpendicular to each other, making an “L” shape. They always stay in this position.

Don't pause the book—we are almost done learning about the cytoskeleton! Before we end the chapter, however, we need to mention two other important jobs that microtubules do, besides their role as a road system: they help a cell to make a copy of itself, and can form

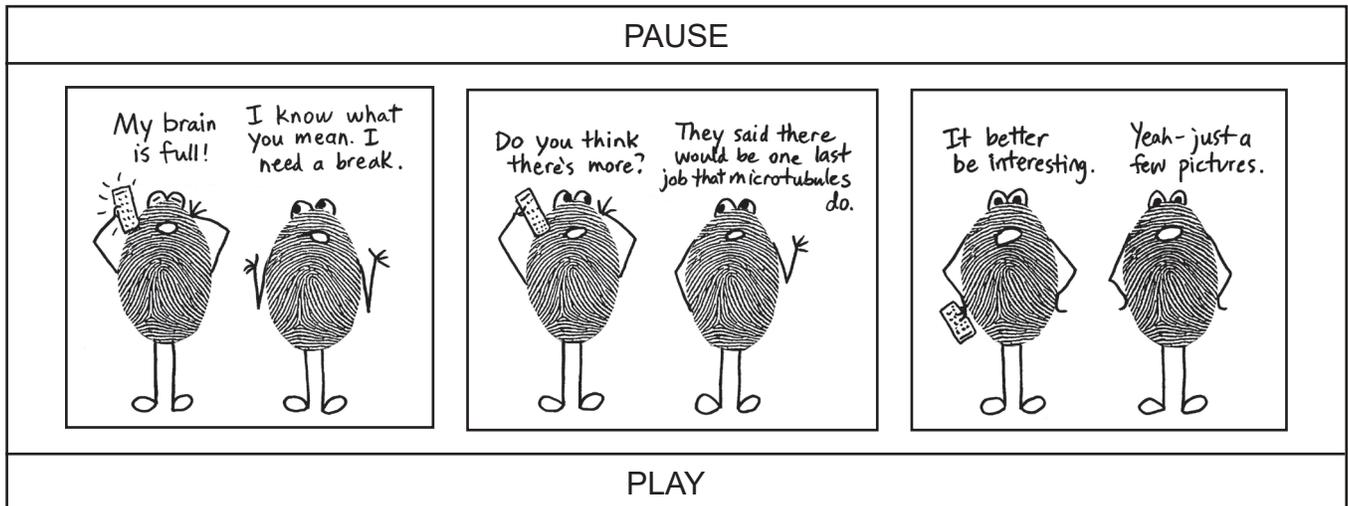
All living organisms must be able to grow, and growth occurs through the process of cell division. Cells are able to split in half, forming two identical copies of themselves. During this duplication process, the cell must make a second copy of its DNA. (We'll learn about DNA in a future chapter, but you probably already know that DNA is like a library, containing all the information the cell will ever need.) The two sets of DNA must be pulled apart and taken to opposite sides of the cell so that when the split occurs, each side will have a full set of DNA.

First, the cell duplicates its centrosome so now it has two of them. The centrosomes go to opposite sides of the cell, as shown in diagram (1). Meanwhile, the DNA duplicates itself inside the nucleus. During the duplication process, the DNA coils up into long sticks called chromosomes. The covering around the nucleus dissolves so that the chromosomes are sitting out in the open in the middle of the cell. The rest of the diagrams have all the other cell parts removed so that we can focus only on what happens to the chromosomes.

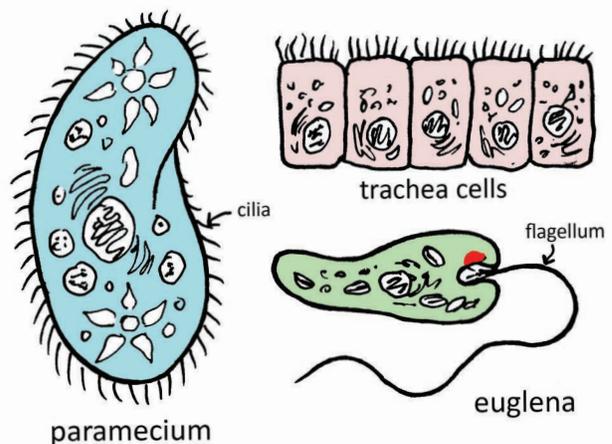
The two sets of chromosomes must be separated and pulled to opposite sides of the cell. In diagram (2), we see the centrosomes form a shape called a **spindle**, which is made from microtubules and looks a bit like an American football. In the middle of the spindle, the microtubules attach to the chromosomes. The microtubules then begin to pull the chromosomes apart, as shown in diagram (3). The pulling is caused by the microtubules beginning to disassemble themselves so they get shorter and shorter. Finally, the two sets of chromosomes are completely separated and arrive at opposite ends of the cell, as shown in diagram (4). The cell is now ready to split in the middle and form two independent cells. Microfilaments will help do the pinching in the middle.



We will study this more in a later chapter. The main point we need to learn now is that microtubules play an important role in cell division by forming a spindle that pulls chromosomes apart.



Microtubules are used in some specialized cells to make things that look like hairs or tails. The hairs are called **cilia** and the tails are called **flagella**. These structures allow the cell to move by acting like paddles (cilia) or propellers (flagella). Cilia are used by single-celled animals like the paramecium, but are also found in our own bodies in the cells that line our trachea (the tube that goes down into our lungs). Flagella are used by many single-celled animals, but are also found in sperm cells made by most living organisms.



Can you remember what you read? If you can't think of the answer, go back and read that part of the chapter again until you find the answer.

- 1) What is the fluid inside a cell called? _____ or _____
- 2) Which one is made of a protein called actin? a) microtubules b) microfilaments c) intermediate filaments
- 3) Which one of these (as far as we know) is NOT something a microfilament might do?
a) cause a muscle fiber to move b) act like a road for motor proteins
c) help a cell to divide in half d) allow the cell to move using pseudopods
- 4) TRUE or FALSE? The only cells that move using "ameboid" motion are single-celled organisms like the ameba.
- 5) Which one of these is attached to the membrane using anchor proteins in the membrane?
a) microfilaments b) intermediate filaments c) microtubules d) all of these e) none of these
- 6) Which of these motor proteins walks outward, towards the edge of the cell? a) kinesin b) dynein
- 7) Which part of a motor protein touches the microtubule highways? a) tails b) feet c) heads
- 8) How long (as far as we know) is the lifetime of a motor protein? a) days b) weeks c) months d) years
- 9) How fast (as far as we know) can a motor protein travel?
a) one step per second b) one step per minute c) 100 steps per second d) 100 steps per minute
- 10) What tiny energy molecule does a motor protein need in order to move? (three letters) ____ _
- 11) Which one of these does the cytoskeleton NOT do?
a) form new phospholipid membranes b) help the cell maintain its shape
c) transport things across the cytoplasm d) form pseudopods
- 12) The protein unit that microtubules are made of is called: t_____.
- 13) A pair of molecules that is bound together is called a d_____.
- 14) How many protein units are need to form a microtubule circle? a) 8 b) 9 c) 11 d) 12 e) 13
- 15) Which of these word roots means "body"? a) cyto b) soma c) pseudo d) pod
- 16) A centrosome is made of two _____ in a blob of protein gel.
- 17) What does the centrosome do? a) acts as a gathering point for all the proteins floating around the cell
b) builds microtubules c) organizes microtubules d) All of these e) b and c
- 18) What does the spindle do? a) pulls chromosomes apart b) makes centrosomes
c) gives shape to the cell d) duplicates chromosomes
- 19) Which type of fibers help the cell to pinch in the middle and form two new cells?
a) microfilaments b) intermediate filaments c) microtubules
- 20) Microtubules are used by specialized cells to make structures (cilia and flagella) that allow them to:
a) divide in half b) be identified by other cells c) use oxygen d) move

ACTIVITY 3.1 “Must-watch” videos

NOTE: The original posters of the videos can decide to take down their videos. In some cases, someone else will put the video back up again, but the address will have changed. Check the Cells playlist for these videos, but if they are not there, try searching for them using key words.

1) “A Day in the Life of a Motor Protein”

This video has over a million views on YouTube. (If you can’t access YouTube, check for it on other videos streaming services.) A biology lab at the University of Utrecht, in the Netherlands, put together an informative and marvelously funny animated film about kinesin and dynein. The cell in which these particular motor proteins live is a nerve cell, so the film starts out with a little information about this type of cell.

2) “The workhorse of the cell: Kinesin”

This video also has a lot of views, so it should pop right up in a search. The animation is fabulous and will bring to life everything you read about kinesins in this chapter.

3) “White blood cell chases a bacteria”

Another video with millions of views and posted from multiple sources. White blood cells use their cytoskeleton to change their shape very quickly. In this video clip you can see a white blood cell chasing some bacteria. It does catch one at the end.

WHILE YOU ARE AT THE PLAYLIST, CONSIDER WATCHING THE OTHER VIDEOS ABOUT THE CYTOSKELETON.

ACTIVITY 3.2 Kinesin vs. Dynein strategy game

This is a two player game. It takes only a few minutes to play. The point of playing the game is to reinforce the fact that motor proteins go in only one direction. **Kinesin (*kin-EE-sin*) goes away from the nucleus, and dynein (*die-nin*) goes towards it.** The board represents a cell with a very simple microtubule arrangement. (Technically, we maybe should have added the centrosome because it is the microtubule organizing center, but the centrosome is very close to the nucleus, so for the sake of simplicity it is easier to show just the nucleus.)

You will need eight coins. Mark four of them with the letter K, and the other four with the letter D. You can use a permanent marker, or you could write the letters on paper circles and tape them on. If you have “sticky notes,” you could cut pieces from the sticky strip of the note. (Using coins will give the tokens some weight so that if someone coughs or sneezes, the tokens won’t blow off the board.)

Put the K tokens on the circles that are close to the nucleus. The goal of the K player will be to get the tokens out to the circles near the plasma membrane.

Put the D tokens on the circles that are close to the outer membrane. The goal of the D player will be to get all the token into the circles close to the nucleus.

Players will take turns making a move. The K pieces can ONLY go either away from the nucleus, or side to side, around the circle that they are currently on. The D pieces can ONLY go either towards the nucleus or side to side, around the circle that they are currently on. Players MUST make a move on each turn. Remember, the tokens can’t go “backwards.” Once they have advanced to another ring, they can’t go back. They can go around that ring, but they can’t go back to the previous one they were on.

The first player to get all their tokens to their destination wins the round.

KINESIN VERSUS DYNEIN

