Unit **2A**

Chapter 3
Cells exchange materials

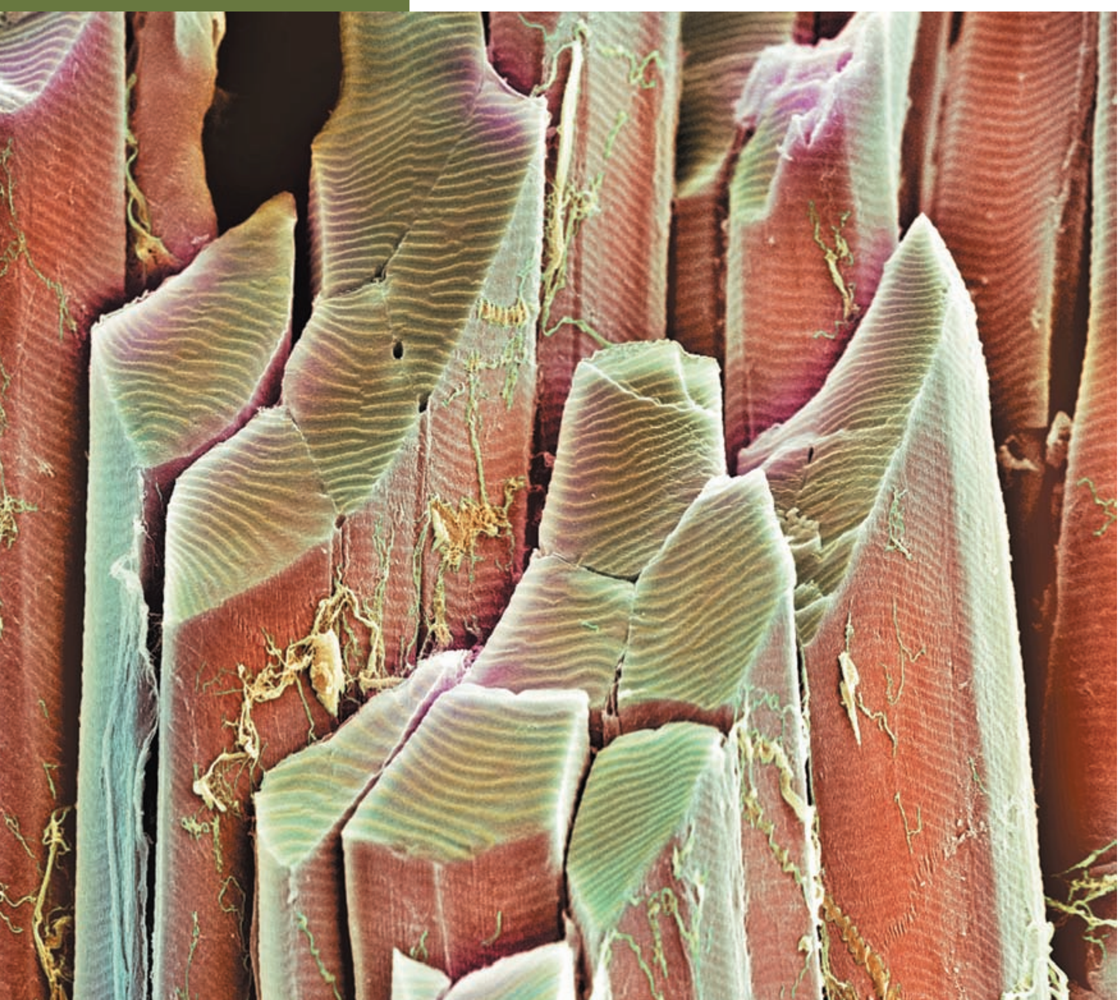


Figure 3.1 Cells come in a variety of shapes and sizes, such as these striated muscle fibres

Unit content

Cells metabolism and regulation

Cellular structures provide for exchange of materials.

Transport:

- structure of the cell membrane as it relates to transport of materials
- methods of transporting materials including diffusion, facilitated diffusion, osmosis, active transport, endocytosis and exocytosis
- factors affecting exchange of materials including SA/V ratio, concentration gradients.

All living organisms, including humans, are made up of cells and materials produced by cells. This is a basic principle of biology and is known as the **cell theory**.

The structure of an organism and the way in which it functions results from the activities of all of its cells. There are trillions of cells in the human body and everything we do results from the combined and coordinated actions of our cells. Each cell, however, is an individual unit with requirements that must be satisfied if it is to function normally.

Cell requirements

For normal functioning, cells in the human body need to be in a stable environment—they must have a continual supply of the materials they need and continual removal of materials they produce.

The immediate environment of a cell is the fluid that surrounds it, known as the **tissue fluid** or **extracellular fluid**. Even cells that appear to be very close together when observed under a microscope will have a thin layer of fluid between them. There is continual exchange of materials between cells and the tissue fluid.

Body systems work together to make sure that the cellular environment is kept constant. This is called **homeostasis**. The cells are maintained at a constant temperature and the concentration of fluids around the cell is kept constant.

To carry out their functions cells need certain substances that must be taken in from the tissue fluid. As substances are processed within the cell, materials are then produced which must be removed from the cell. Different cells will have different requirements and different products depending on the particular role of the cell. There are, however, certain substances that all cells require and which all cells produce.

All cells need oxygen for respiration. It is the process of respiration that releases the energy needed for the cell's activities. Also needed for respiration is glucose, the substance that is broken down to release energy. Respiration produces carbon dioxide and water, substances that cannot be allowed to accumulate in the cell.

Many cells produce substances that will be used elsewhere in the body, such as hormones and enzymes. Many other wastes are produced in addition to carbon dioxide. All of these products must be released into the tissue fluid.

How substances get into and out of cells

Each cell is surrounded by a **cell membrane** (see Fig. 3.10), also called a **plasma membrane**. The cell membrane separates the cell contents from the external environment. It is very thin—too thin to be seen clearly with a light microscope. The cell membrane represents a barrier between the cell and its surroundings. Substances that enter or leave the cell must pass through the cell membrane, so the membrane is very important in determining which substances will get into or out of a cell.

Structure of the cell membrane

The cell membrane is composed mainly of lipids and proteins. The lipid molecules contain a phosphate group and are known as **phospholipids**. They are arranged into two layers that make up the single membrane. It is known as a **bilayer**. Proteins are scattered through the bilayer and they carry out most of the functions of the membrane. All the membranes in the cell have a structure that is similar to the cell membrane.

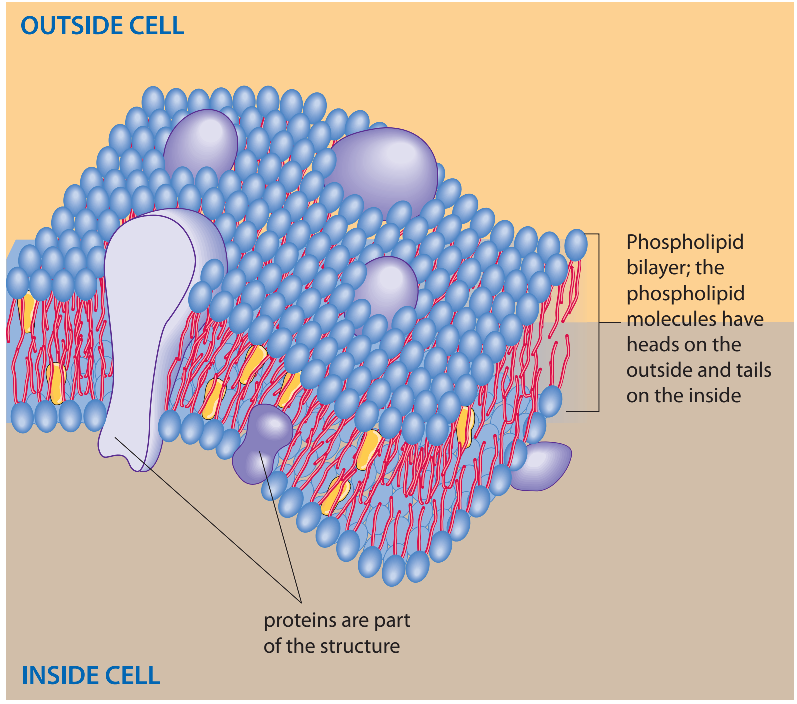


Figure 3.2 The cell membrane showing a phospholipid bilayer and proteins

Transport across the cell membrane

Cell membranes are described as being **differentially permeable**. They allow certain ions and molecules to pass through, but restrict the movement of others. (Differentially permeable membranes may also be called semipermeable or selectively permeable membranes.)

Materials may pass through a cell membrane in a number of different ways. Some transfer mechanisms are **passive processes** which means that the cell's energy, which comes from respiration, does not have to be used. **Active processes** require the cell's energy for the transfer to occur.

There are three basic processes that result in transport of materials into, or out of, a cell:

1. *diffusion*—a passive process resulting from the random movement of ions and molecules, and osmosis (also a passive process), a special case of diffusion where water passes across the membrane
2. *carrier-mediated transport*—process that requires special proteins in the cell membrane; may be passive or active depending on the exact nature of the mechanism
3. *vesicular transport*—process where materials are moved in membrane-bound sacs; an active process.

Find out more about cell membranes at http://www.biology4kids.com/files/cell_membrane.html

Diffusion

Diffusion is the spreading out of particles so that they are evenly distributed over the space available. It occurs in both gases and liquids because the molecules of gases and liquids are constantly moving. They move in random directions and in straight lines until they hit another molecule or the wall of the container. A deflected molecule then continues in a straight line until it hits another obstacle. Molecules moving away from an area where they are concentrated experience fewer collisions than those moving towards the area of higher concentration. They therefore stay on their straight paths longer and move out into areas where the concentration of those molecules is lower. In this way the molecules become evenly spread over the space available. Random movement of molecules continues, but the chances of collision will be the same in whatever direction the molecule is travelling.

Figure 3.3 shows how a sugar cube dissolves in water and how the molecules of sugar spread out until they are evenly spread throughout the water. As the sugar dissolves, the sugar molecules near the cube are more concentrated than those near the surface of the water. The difference in concentration that brings about diffusion is called a **concentration gradient**, or **diffusion gradient**. The greater the difference in concentrations, the 'steeper' the diffusion gradient and the faster diffusion will occur (Fig. 3.4).

The movement of liquid or gas molecules from places of higher concentration to places of lower concentration, along a diffusion gradient, is more correctly called **net diffusion**. There will always be some molecules moving against the diffusion gradient because the movement of molecules is random.

In the example of sugar molecules diffusing in a beaker of water (see Fig. 3.3), the water molecules are also involved in diffusion. When the sugar cube is first placed in the water, there is a lower concentration of water in the sugar cube and a higher concentration of water elsewhere in the beaker. Thus, there is also a diffusion gradient for the water, but it is in the opposite direction to that for the sugar.

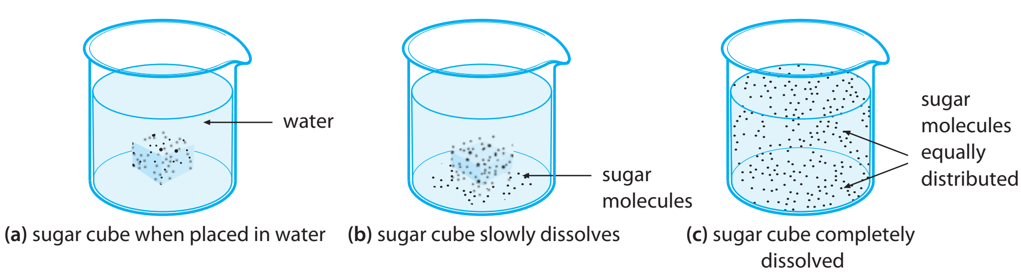


Figure 3.3 Process of diffusion of sugar in a beaker of water

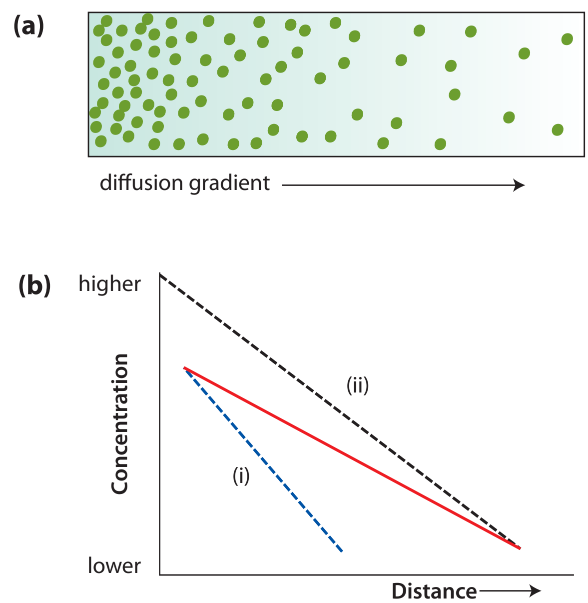
Alcohol, steroids and other fat-soluble substances can easily enter cells because they can diffuse through the lipid portions of the membrane. Oxygen and carbon dioxide can also diffuse through the phospholipid bilayer.

Oxygen diffuses into cells because it is continually used up inside the cell for respiration. The concentration of oxygen inside the cell is therefore lower than the oxygen concentration outside the cell. Due to this concentration difference there is net diffusion of oxygen into the cell.

Carbon dioxide is continually produced inside the cell by respiration. The higher concentration of carbon dioxide inside the cell means that there will be net diffusion of carbon dioxide out of the cell.

To diffuse into a cell, water-soluble molecules must pass through protein channels in the membrane. These channels are very small in diameter so that water and ions can easily get through. Larger molecules are too big to fit through the channels (Fig. 3.5).

Figure 3.4 Diffusion gradient: **(a)** shown pictorially in terms of number of molecules; **(b)** shown graphically (note how **(i)** changing the distance, or **(ii)** changing the concentration difference, alters the 'steepness' of the gradient)



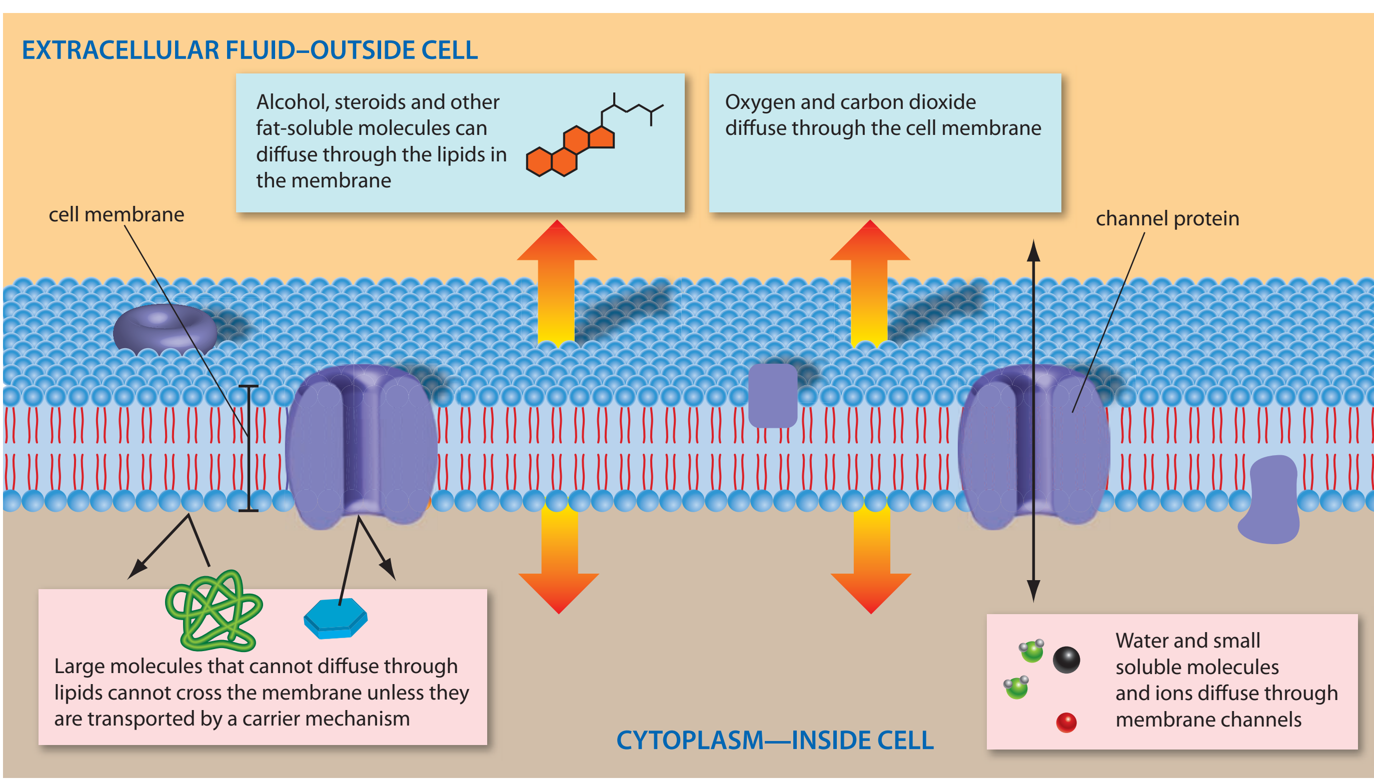


Figure 3.5 Only some substances can diffuse across a cell membrane

Osmosis

Osmosis is a special type of diffusion. It is the diffusion of a solvent through a differentially permeable membrane. As water is the most important solvent in the human body, **osmosis** can be considered to be the diffusion of water across a differentially permeable membrane from a region of higher *water* concentration to a region of lower *water* concentration. The concentration of water depends on how much solute is dissolved in the water.

Osmosis is of particular importance to living cells because the cell membrane is differentially permeable. Such a membrane can be thought of as containing many tiny pores. Small molecules (e.g. water) are able to pass through the pores in the membrane quite easily, but large molecules (e.g. sugar, starch or proteins) are not able to pass through at all. A beaker, divided in two by a differentially permeable membrane, is shown in Figure 3.6. On one side of the membrane is pure water, whereas on the other side is a sugar solution. In the sugar solution some of the space is taken up by sugar molecules so the concentration of water molecules will be less than in the pure water. As water molecules can pass through the membrane they will distribute themselves evenly over the whole beaker, but the sugar molecules will stay on the same side of the membrane. Because of the difference in concentration of water molecules, more water molecules will move from the water to the sugar solution than in the opposite direction. The sugar solution will gain water.

Note that in Figure 3.6 the level of liquid on the water side of the membrane has dropped, whereas that on the sugar side has risen. This higher level on one side of the membrane results in a pressure, known as **osmotic pressure**. The higher the concentration of solute (in this case the sugar), the higher the osmotic pressure.

Water moves into, or out of, a cell depending on the water concentration on each side of the cell membrane.

See these websites for an animation of osmosis and diffusion:

- http://www.biologycorner.com/bio1/diffusion.html
- http://www.stolaf.edu/people/giannini/flashanimat/transport/osmosis.swf

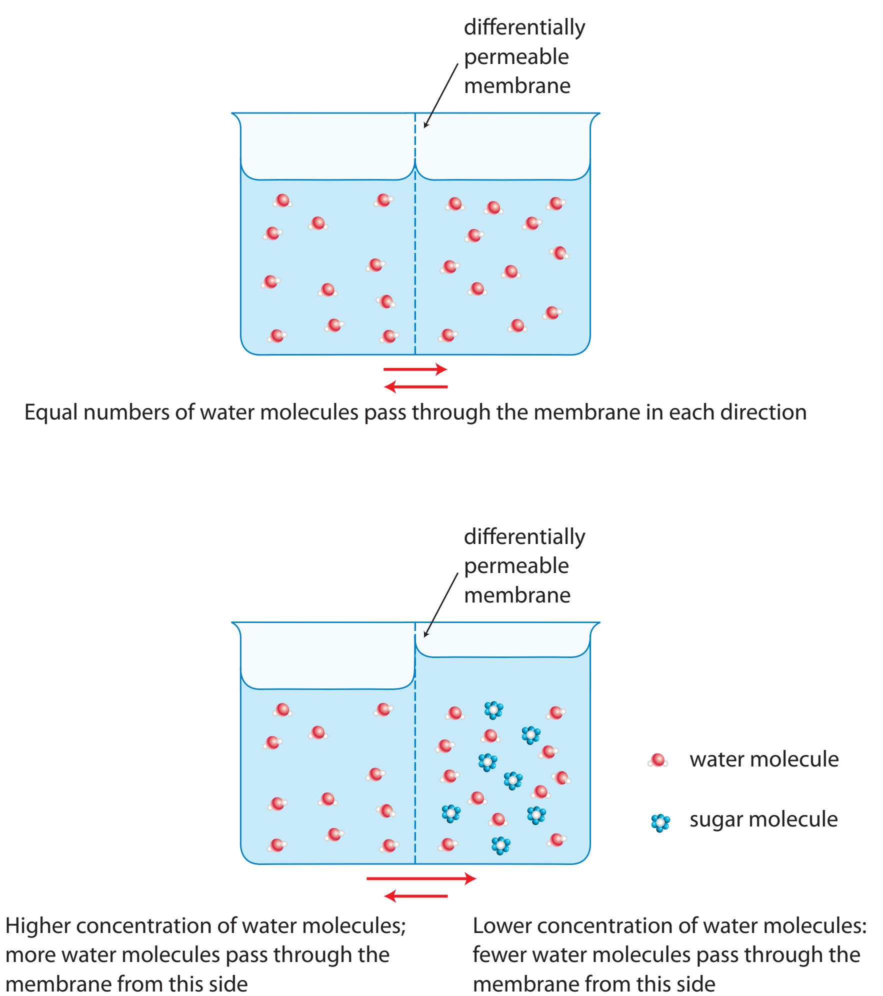


Figure 3.6 Process of osmosis

Carrier-mediated transport

In **carrier-mediated transport** there are special proteins in the cell membrane that bind to an ion or molecule and help it to move across the membrane. These carrier proteins are specific; they usually only work with one particular ion or molecule.

Facilitated diffusion

Many substances that a cell needs, such as glucose and amino acids, have molecules that are too large to fit through the cell membrane by simple diffusion. Such substances can be moved through the membrane by carrier proteins in a process called **facilitated diffusion**. Facilitated diffusion is a passive process that moves substances from a higher concentration on one side of the membrane to a lower concentration on the opposite side.

The transported molecule binds to a carrier protein, which then changes shape, moving the molecule to the opposite side of the cell membrane where it is released (Fig. 3.7). Facilitated diffusion is different from simple diffusion because once all the carrier molecules are in use the process cannot go any faster. With simple diffusion there is no such limitation; the greater the concentration difference, the faster the rate of diffusion.

All cells transport glucose molecules through their membranes by facilitated diffusion.

Active transport

As its name states, active transport is an active process requiring cellular energy. Although energy expenditure is a disadvantage for the cell, the big advantage of active transport is that it can move molecules across the membrane against the concentration gradient; that is, from lower concentration to higher concentration. **Active transport** is therefore the movement of substances across the cell membrane against the concentration gradient using cellular energy. Carrier proteins are involved in a similar way to facilitated diffusion. Substances such as amino acids and certain ions that are already more concentrated inside the cell can still be absorbed. In the same way, some less concentrated materials can be exported from the cell.

The energy for the cell's active processes is released by the mitochondria (see Fig. 3.10). At the **mitochondria** cellular respiration breaks down glucose to release energy that the cell can use for its activities.

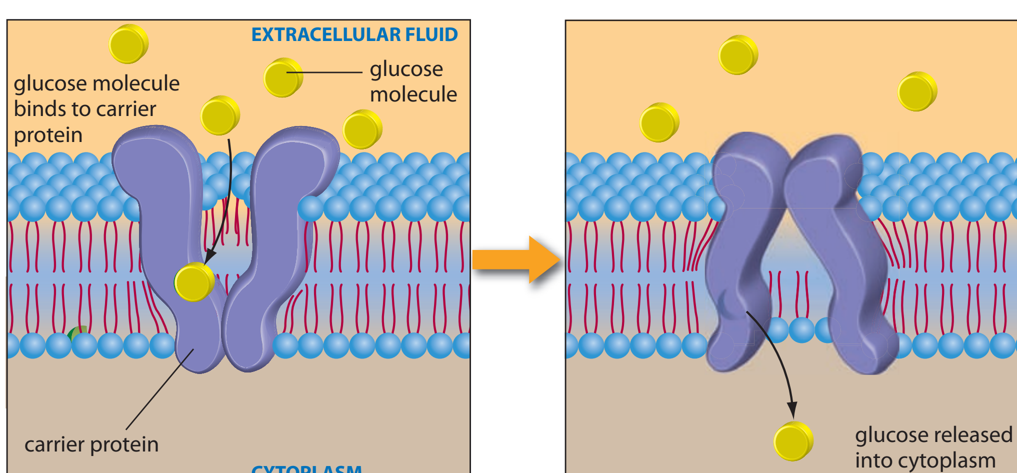


Figure 3.7 Process of facilitated diffusion

EXTENSION

A mechanism called the sodium–potassium pump is an example of active transport that occurs in the plasma membrane of all cells. The sodium–potassium pump uses about half of the energy that you consume each day.

Investigate:

- how the sodium–potassium pump works
- the functions of the sodium–potassium pump.

Vesicular transport

Vesicular transport is an active process in which materials move into or out of the cell enclosed as vesicles. **Vesicles** are bubble-like structures surrounded by a membrane. They can form at the cell membrane or can fuse with the membrane. Solid particles, droplets of fluid or many molecules at a time can be moved across the membrane in vesicles. Vesicular transport is also known as **bulk transport** because large quantities of materials can be transported in this way.

There are two basic types of vesicular transport—endocytosis and exocytosis.

Endocytosis

Endocytosis is when a cell surrounds some extracellular material with a fold of the cell membrane. The enfolding membrane then breaks away, and the material is enclosed within the cell in the form of a small membrane-bound vesicle (Fig. 3.8).

There are two forms of endocytosis. Where the material engulfed by the cell includes solid particles, it is known as **phagocytosis** (cell eating). If the material taken in is a liquid, the process is called **pinocytosis** (cell drinking). All cells carry out pinocytosis but phagocytosis is performed only by specialised cells. White blood cells, for example, use phagocytosis to engulf bacteria at the site of an infection.

For more information on active transport, phagocytosis and pinocytosis see the web pages at http://www.biology4kids.com/map.html

Exocytosis

If the contents of a vesicle are pushed out through the cell membrane, the process is called **exocytosis**. The membrane around the vesicle fuses with the cell membrane and the vesicle contents are passed to the exterior (Fig. 3.9).

Material passed out of a cell by exocytosis may be a waste product or may be a substance that the cell has made for use elsewhere. Milk from breast cells, saliva from salivary gland cells and digestive enzymes from cells lining the small intestine are all exported from the cells by exocytosis.

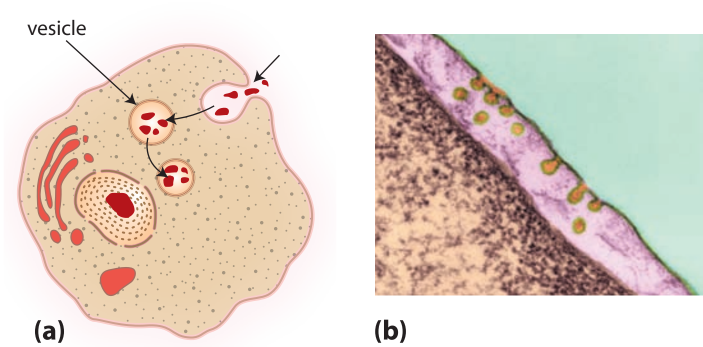
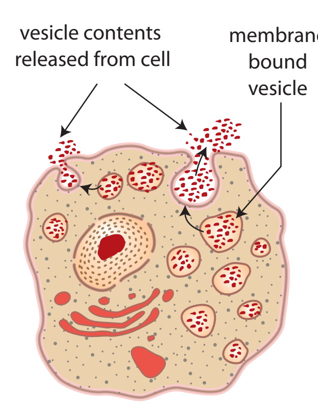


Figure 3.8 **(a)** The process of endocytosis; **(b)** electron micrograph of a cell lining a blood capillary. The cell is taking in droplets of liquid by endocytosis (pinocytosis)

Figure 3.9 The process of exocytosis



EXTENSION

The systems of the body work together to keep the internal environment as stable as possible. In a stable environment cells can function at their optimum level.
Investigate what can happen to cells if:

- their temperature becomes too high or too low
- they become dehydrated
- there is inadequate oxygen
- carbon dioxide is allowed to accumulate.

Movement within the cell

Molecules and ions mostly move within the cell by diffusion. Remember that diffusion is the spreading of particles so that they are evenly distributed over the space available. Thus, as molecules of a substance are used up in one part of the cell other molecules will spread to take their place. For example, as oxygen is used up by the mitochondria for respiration a lower concentration of oxygen will be created. Oxygen will diffuse into the area of lower concentration from areas of higher concentration within the cell.

The **endoplasmic reticulum** is a network of parallel membranes within the cell (Fig. 3.10). It is used to transport substances within the cell, particularly proteins that the cell has made. These are transported to the **Golgi apparatus** (also called the Golgi body) for secretion from the cell.

Microtubules are very fine tubes that help to maintain the shape of the cell and to hold the organelles in place. They also act like railway tracks and guide organelles or molecules to particular places within the cell. Microtubules are not permanent structures but are able to be broken down or built up as needed in the various parts of the cell.

Why are cells so small?

Most human cells are between 10 and 15 micrometres (μm) in diameter (1 μm is one-thousandth of a millimetre). Nerve cells may have extensions that are up to a metre long and muscle cells may be up to 30 cm long. However, both nerve and muscle cells are too thin to be seen with the naked eye. Human egg cells have a diameter of up to 100 μm and may be just visible to the naked eye (Fig. 3.11).

There is a limit to how big a cell can be. Remember that all the requirements of a cell, and all the products of a cell, must pass across the cell membrane. Thus, the relationship between the surface area of the cell and the volume is all important. Imagine that an apple is a cell. If the apple is cut in half, each half has half of the original volume, but each half has *more* than half of the original surface area. Cutting the apple in half has created extra surface area because of the two cut surfaces. If you continue to cut the apple into smaller and smaller pieces, the surface area to volume ratio of the pieces gets bigger and bigger. In the same way a small cell will have a larger surface to volume ratio than a large cell.

Figure 3.12 illustrates how doubling the length of the side of a cube-shaped cell results in *eight* times the volume but only *four* times the surface area. As a cell grows its ability to exchange enough materials to support its increasing volume is diminished because the volume increases at a greater rate than the surface area. A large cell could not support itself because it would not have enough membrane surface to absorb the nutrients required, and remove the wastes produced, by its large volume. To function effectively most cells have to be microscopic.

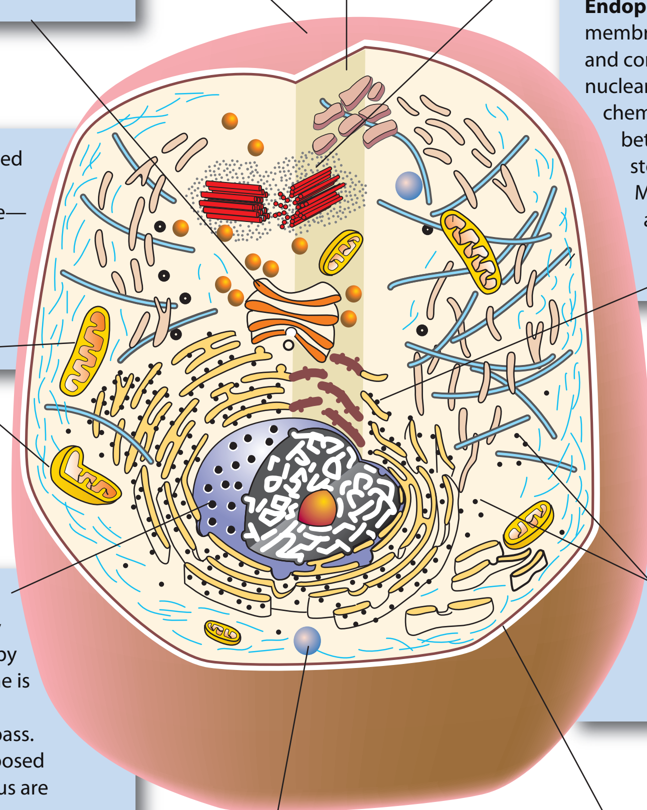


Figure 3.10 Model of cell structure and functions

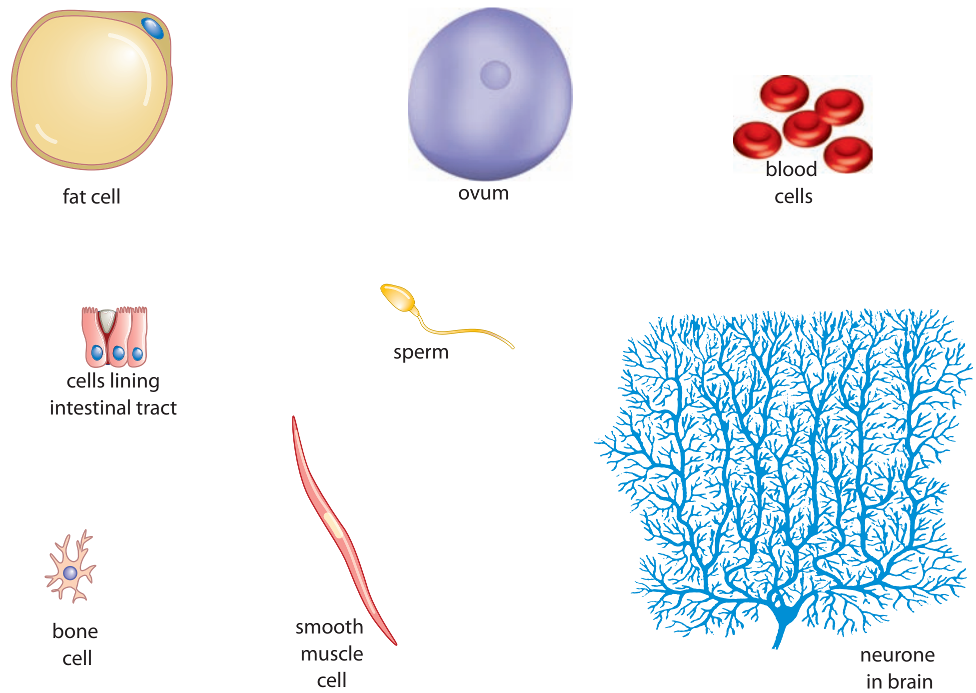
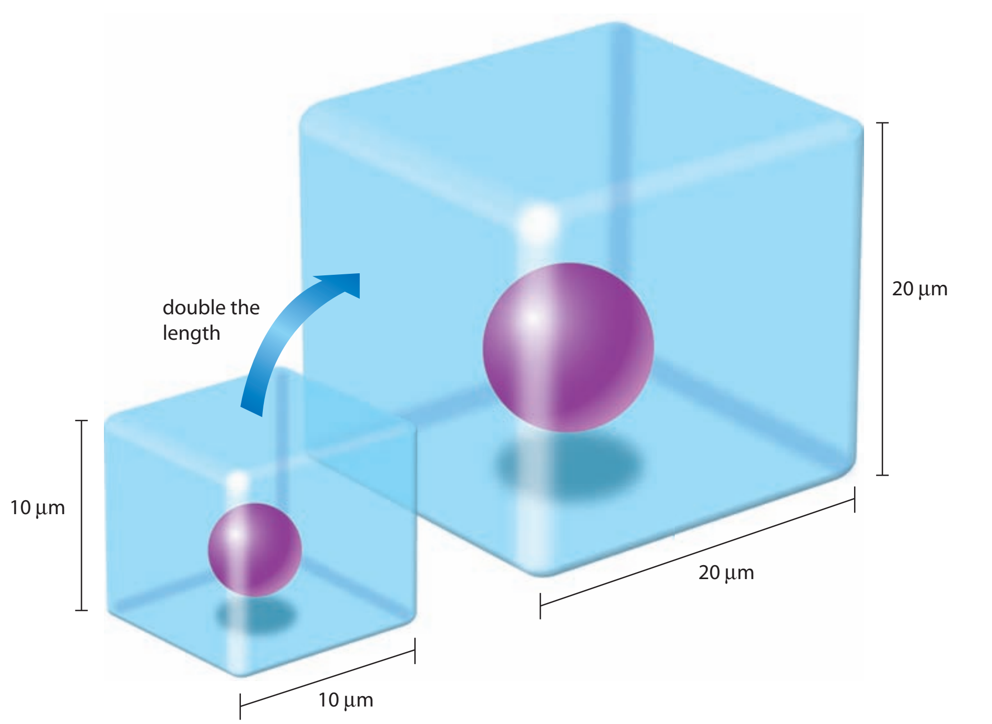


Figure 3.11 Human cells have varied sizes and shapes



Length = 10 µm
Surface area = 10 µm × 10 µm × 6 = 600 µm^2
Volume = 10 µm × 10 µm × 10 µm = 1000 µm^3

Length = 20 µm
Surface area = 20 µm × 20 µm × 6 = 2400 µm^2
Volume = 20 µm × 20 µm × 20 µm = 8000 µm^3

Figure 3.12 The relationship between the surface area of a cell and its volume. When the diameter of a cell is doubled its volume is eight times greater but its surface area is only four times greater

Working scientifically

Activity 3.1 Diffusion through a differentially permeable membrane

To get into and out of cells, substances must pass through the differentially permeable cell membrane. This activity will give you some understanding of the properties of differentially permeable membranes.

You will need

Cellulose tubing; glass tubing; 250 mL beaker; retort stand, clamp and boss; small elastic band; marking pen; starch suspension, 10%; iodine solution (iodine-potassium-iodide, I_2KI)

What to do

1. Cut a length of cellulose tubing about 12 cm long.
2. Tie a tight knot in the tubing near one end. Wet the tubing and open it so that it forms a bag.
3. Add starch suspension to the bag until it is nearly full.
4. Use an elastic band to attach the cellulose bag to the end of the glass tubing as shown in the diagram (Fig. 3.12). Make sure your elastic band is very tight so that there can be no leaks.
5. Rinse the cellulose bag and glass tubing under the tap to remove any starch from the outside.
6. With a marking pen, mark the level of starch suspension in the bag.
7. Lower the bag into a beaker of water and hold the tubing erect using a retort stand and clamp.
8. Add iodine solution to the water outside the bag until the water is pale yellow.
9. Leave the set-up to stand for at least 40 minutes and, if necessary, overnight.

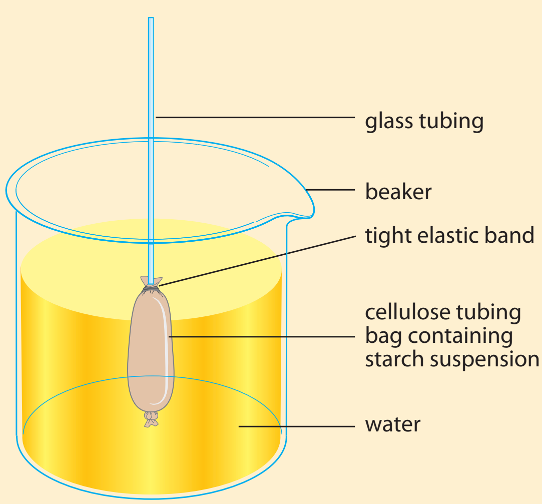


Figure 3.13 Apparatus for the investigation

Studying your results

Record:

- any change in the level of solution inside the cellulose bag or glass tubing
- any change in colour of the solution in the bag and the solution outside the bag.

Use your results to discuss and record answers to the following questions.

1. Do you have any evidence that any molecules passed from the beaker into the bag? Describe any such evidence.
2. Do you have any evidence that any molecules moved from inside the bag to the outside? Explain your answer.
3. Which has larger molecules, starch or iodine-potassium-iodide? Explain your answer.
4. Use the description of osmosis in this chapter to explain the changes that occurred in the experimental set-up.
5. If the cellulose bag containing starch suspension were a model of a cell, what part of the cell would be represented by the cellulose bag itself?
6. Predict what would happen if an isolated animal cell were placed in distilled water.

Activity 3.2 Using a microscope to estimate cell diameter

This activity will give you practice in using a microscope to estimate the diameter of a cell. You may have to work with a partner.

You will need

Microscope and microscope lamp; prepared microscope slides, minigrid or piece of millimetre graph paper (or clear plastic ruler)

What to do

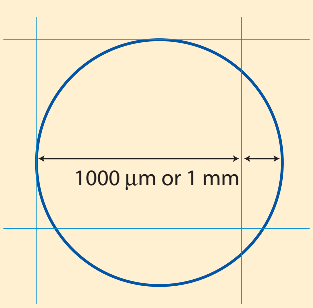


Figure 3.14 Estimating field diameter using a minigrid

1. Place a minigrid, or a slide with a piece of millimetre graph paper (or a clear plastic ruler), on the stage of the microscope. With the microscope on low power, lower the body tube until the objective lens almost touches the slide. While looking through the ocular lens use the coarse adjustment to slowly raise the body tube until the specimen comes into view. With the fine adjustment focus as sharply as possible. (Never focus down while you are looking through the ocular lens. The objective lens may hit the slide and break it or the lens may be scratched.)
2. Move the slide so that one of the grid lines is on the very left of the field of view (Fig. 3.14). As the grid lines are 1 mm apart you can estimate the field of view using low (or medium) power.
3. If your microscope has three objective lenses, use the same method to measure the field diameter when the medium power objective lens is in place.
4. Remove the minigrid and place a prepared microscope slide on the stage of the microscope so that the material you wish to examine is over the hole in the stage.
5. Focus the microscope on low (or medium) power. Adjust the diaphragm so that you can see the maximum amount of detail. Note that you can often see more detail with a reduced light intensity, especially if the cells are almost transparent.
6. Turn the revolving nosepiece so that the high-power objective lens is in line with the barrel. If you do this carefully the microscope should remain in focus or almost in focus.

Studying your observations

1. What was the field diameter on low power? If your microscope has a medium power objective lens, what was the field diameter on medium power?
   As magnification of a microscope is increased, field diameter decreases. For example, if the field diameter at a magnification of ×50 is 2000 μm, doubling the magnification to ×100 halves the field diameter, which will then be 1000 μm.
   A simple way to calculate high power field diameter is:

$$\text{high power field diameter} = (\text{low power magnification} \div \text{high power magnification}) \times \text{low power field diameter}$$

2. Calculate the field diameter on high power (with the same ocular lens as you used for low power).
3. Using the field diameters that you have calculated, estimate the diameter of the cells on the prepared slide.

Activity 3.3 What size is it?

This activity will give you some practice in calculating the size of cells.
Figure 3.15 shows some cells as seen with the high power of a microscope.

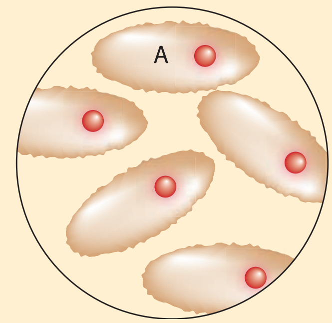


Figure 3.15 Cells seen with the high power of a microscope

1. If the field diameter is 0.5 mm, what is the approximate length and breadth of cell A in millimetres and in micrometres?
2. If the objective lens was changed from ×40 to ×10, what would be the new field diameter?
3. How many cells like cell A would fit end-to-end across the field with this new field diameter?

A student drew the cell shown in Figure 3.16. The actual length of the cell was 100 μm.

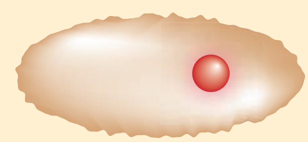


Figure 3.16 This cell is 100 μm long

4. What is the magnification of the student's drawing?
5. Estimate the length and width of the cell shown in Figure 3.17.
6. Estimate the diameter of the nucleus of the cell.
7. How many of these cells would fit side-by-side across a field of view that has a diameter of 1.6 mm?

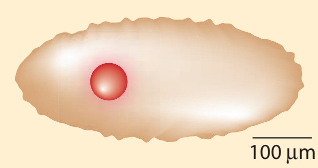


Figure 3.17

REVIEW QUESTIONS

1. (a) What is homeostasis?
   (b) What variables have to be kept relatively constant to achieve homeostasis of a cell's environment?
2. List the substances that:
   (a) are required by all cells
   (b) have to be removed from all cells.
3. Describe the structure of a cell membrane.
4. What is diffusion? In your answer explain the term 'diffusion gradient'.
5. What is a differentially permeable membrane? How would such a membrane differ from one that is completely permeable?
6. What is osmosis? In your answer explain what is meant by 'osmotic pressure'.
7. What 'carriers' are involved in carrier-mediated transport? Explain the role of the carrier in this form of transport.

8. Explain the difference between facilitated diffusion and active transport.
9. **(a)** What is vesicular transport?
   (b) Explain the difference between endocytosis and exocytosis.
   (c) Explain the difference between phagocytosis and pinocytosis.
10. **(a)** What is the difference between a passive process and an active process?
    (b) List the forms of transport described in this chapter in two columns, one for passive processes and one for active processes.

APPLY YOUR KNOWLEDGE

1. Explain how the structure of the cell membrane makes it permeable to some molecules but not to others.
2. Explain why, in the lungs, oxygen diffuses from the air into the blood but carbon dioxide diffuses from the blood into the air.
3. A red blood cell placed in distilled water swells up and bursts but a red blood cell placed in sea water (about 3% salt) shrivels. Explain why this happens.
4. Patients who have suffered severe blood loss or dehydration have to be given large volumes of fluid. A fluid that is often given is a 0.9% solution of sodium chloride, known as *normal saline*. Why is saline solution given rather than just plain water?
5. During digestion the concentration of acid in the stomach rises to several times that found in the cells of the stomach lining. Explain which transport process would be responsible for this situation.
6. The hormone insulin activates glucose carriers in the cell membrane of muscle cells, fat storage cells and many other types of cells. People who suffer from diabetes mellitus type 1 do not produce enough insulin. The amount of glucose in their blood can be abnormally high and they excrete glucose in the urine. Why would diabetes sufferers have abnormally high blood glucose levels?
7. Explain why large mammals, such as whales and elephants, have cells that are the same size as small mammals, such as mice.