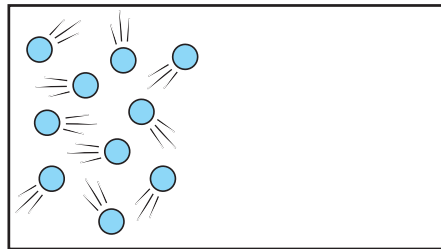


Movement In and Out of Cells

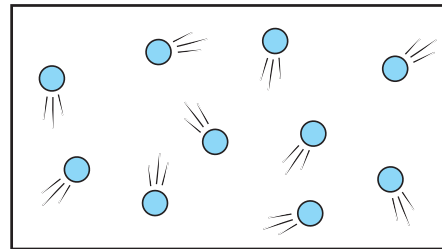
Diffusion:

Diffusion is the net movement of molecules and ions from a region of their higher concentration to a region of their lower concentration down a concentration gradient, as a result of their random movement.

The molecules of a gas such as oxygen are moving about all the time. So are the molecules of a liquid or a substance such as sugar dissolved in water. As a result of this movement, the molecules spread themselves out evenly to fill all the available space.



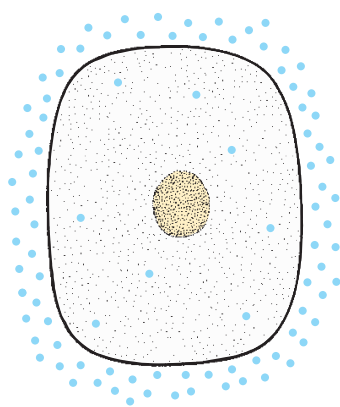
molecules moving about



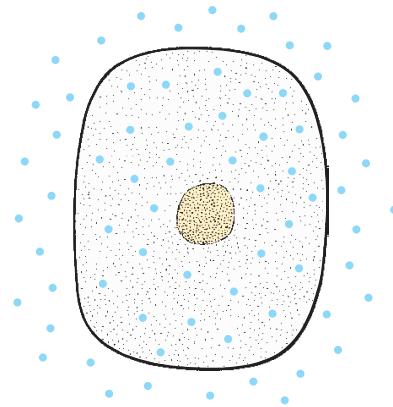
become evenly distributed

This process is called **diffusion**. One effect of diffusion is that the molecules of a gas, a liquid or a dissolved substance will move from a region where there are a lot of them (more concentrated) to regions where there are few of them (less concentrated) until the concentration everywhere is the same.

Part (a) is a diagram of a cell with a high concentration of molecules (e.g. oxygen) outside and a low concentration inside. The effect of this difference in concentration is to make the molecules diffuse into the cell until the concentration inside and outside is the same, as shown in part (b).



(a) greater concentration outside cell



(b) concentrations equal on both sides of the cell membrane

Whether this will happen or not depends on whether the cell membrane will let the molecules through. Small molecules such as water (H_2O), carbon dioxide (CO_2) and oxygen (O_2) can pass through the cell membrane fairly easily. So, diffusion tends to equalize the concentration of these molecules inside and outside the cell all the time.

When a cell uses oxygen for its aerobic respiration, the concentration of oxygen inside the cell falls and so oxygen molecules diffuse into the cell until the concentration is raised again. During tissue respiration, carbon dioxide is produced and so its concentration inside the cell increases. Once again diffusion takes place, but this time the molecules move out of the cell. In this way, diffusion can explain how a cell takes in its oxygen and gets rid of its carbon dioxide.

The Importance of Diffusion of Gases and Solutes:

For Gases: Most living things require a reliable source of oxygen for respiration. This moves into the organism by diffusion down a concentration gradient. Small animals with a large surface area to volume ratio may obtain oxygen through their body surface. Larger animals rely on gas exchange organs such as lungs or gills, which provide a large surface area for gas exchange, and a circulatory system to transport the oxygen to all their cells. Carbon dioxide, produced during aerobic respiration, is potentially toxic if it builds up. It is removed using the same mechanisms, again by diffusion.

Photosynthetic plants need carbon dioxide for making their food. This diffuses through the stomata in the leaves into the air spaces in the mesophyll, eventually reaching the palisade cells. Oxygen, produced during photosynthesis, along with water vapor from the transpiration stream, diffuses out of the leaf through the stomata. The rate of diffusion of water vapor depends on the temperature, humidity and wind speed. Any oxygen needed for respiration (some is generated by photosynthesis) and carbon dioxide produced (some is used up by photosynthesis) also diffuses through the stomata of the leaves.

Nitrogen is the commonest gas in the atmosphere. (78% of the air is nitrogen.) Nitrogen gas also enters the bloodstream by diffusion, but it is not used by the body. It is an inert (unreactive) gas so, under normal circumstances, it causes no problems. However, divers are at risk. As a diver swims deeper, the surrounding water pressure increases and this in turn raises the pressure in the diver's air tank. An increase in nitrogen pressure in the air tank results in more nitrogen diffusing into the diver's tissues, the amount going up the longer the diver stays at depth. Nitrogen is not used by the body tissues, so it builds up. When the diver begins to return to the surface of the water, the pressure decreases and the nitrogen can come out of solution, forming bubbles in the blood if the diver ascends too quickly. These bubbles can block blood flow and become lodged in joints resulting in a condition called **decompression sickness**, or **the bends**. Unless the diver rises slowly in planned stages, the effect of the nitrogen bubbles is potentially lethal and can only be overcome by rapid recompression.

Solutes: Mineral ions in solution, such as nitrates and magnesium, are thought to diffuse across the tissues of plant roots, but most are absorbed into the roots by active transport.

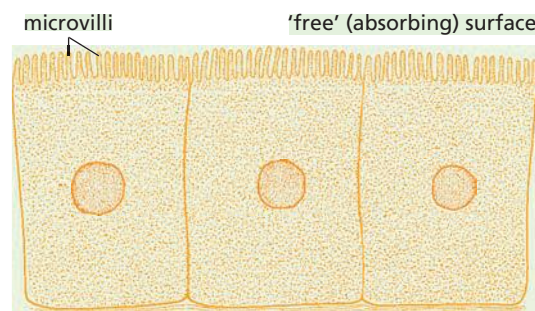
In the ileum, water-soluble vitamins such as vitamin B and vitamin C are absorbed into the bloodstream by diffusion.

In the kidneys, some solutes in the renal capsule, such as urea and salts, pass back into the bloodstream by diffusion. Initially, glucose is reabsorbed by diffusion, but active transport is also involved. Dialysis machines use diffusion to remove small solutes (urea, uric acid and excess salts) from the blood.

Rates of Diffusion:

Molecules and ions in liquids and gases move around randomly using **kinetic energy** (energy from movement). The speed with which a substance diffuses through a cell wall or cell membrane will depend on temperature and many other conditions including the distance it has to diffuse, the difference between its concentration inside and outside the cell, the size of its molecules or ions and the surface area across which the diffusion is occurring.

1. Surface area: If 100 molecules diffuse through 1 mm² of a membrane in 1 minute, it is reasonable to suppose that an area of 2 mm² will allow twice as many through in the same time. Thus, the rate of diffusion into a cell will depend on the cell's surface area. The greater the surface area, the faster is the total diffusion. Cells which are involved in rapid absorption, such as those in the kidney or the intestine, often have their free surface membrane formed into hundreds of tiny projections called **microvilli** which increase the absorbing surface.

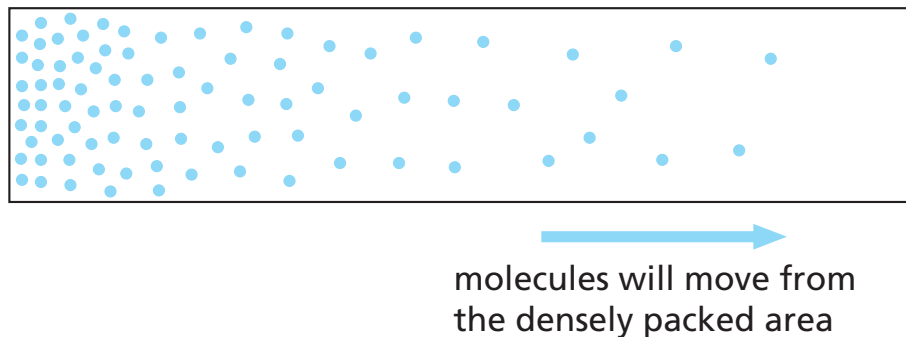


The shape of a cell will also affect the surface area. For example, the cell in (a) has a greater surface area than that in (b), even though they each have the same volume.



2. Temperature: An increase in temperature causes an increase in the kinetic energy which molecules and ions possess. This enables them to move faster, so the process of diffusion speeds up.

3. Concentration Gradient: The bigger the difference in the concentration of a substance on either side of a membrane, the faster it will tend to diffuse. The difference is called a **concentration gradient** or **diffusion gradient**. If a substance on one side of a membrane is steadily removed, the diffusion gradient is maintained. When oxygen molecules enter a red blood cell they combine with a chemical (hemoglobin) which takes them out of solution. Thus, the concentration of free oxygen molecules inside the cell is kept very low and the diffusion gradient for oxygen is maintained.



4. Distance: Cell membranes are all about the same thickness (approximately $0.007\text{ }\mu\text{m}$) but plant cell walls vary in their thickness and permeability. Generally speaking, the thicker the wall, the slower the rate of diffusion. When oxygen diffuses from the alveoli of the lungs into red blood cells, it has to travel through the cell membranes of the alveoli, the blood capillaries and the red blood cells in addition to the cytoplasm of each cell. This increased distance slows down the diffusion rate.

5. Size of Molecules or Ions: In general, the larger the molecules or ions, the slower they diffuse. However, many ions and molecules in solution attract water molecules around them and so their effective size is greatly increased. It may not be possible to predict the rate of diffusion from the molecular size alone.

Controlled Diffusion:

Although for any one substance, the rate of diffusion through a cell membrane depends partly on the concentration gradient, the rate is often faster or slower than expected. Water diffuses more slowly and amino acids diffuse more rapidly through a membrane than might be expected. In some cases, this is thought to happen because the ions or molecules can pass through the membrane only by means of special pores. These pores may be few in number or they may be open or closed in different conditions.

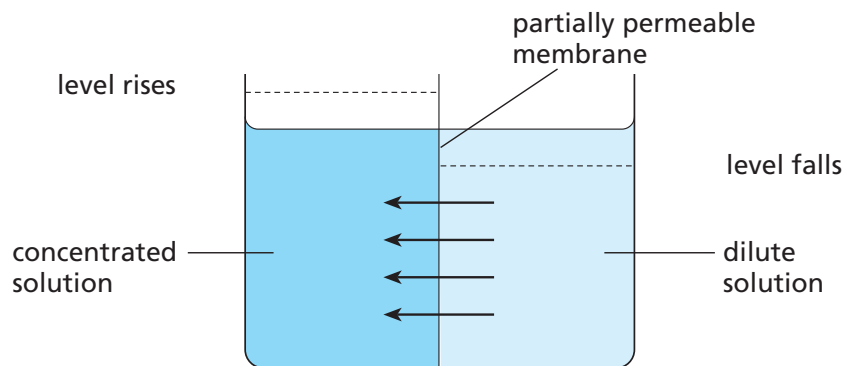
In other cases, the movement of a substance may be speeded up by an enzyme working in the cell membrane. So, it seems that 'simple passive' diffusion, even of water molecules, may not be so simple or so passive after all where cell membranes are concerned.

When a molecule gets inside a cell there are a great many structures and processes which may move it from where it enters to where it is needed. Simple diffusion is unlikely to play a very significant part in this movement.

Osmosis:

Osmosis is the net movement of water molecules from a region of higher water potential (a dilute solution) to a region of lower water potential (a concentrated solution) through a partially permeable membrane.

If a dilute solution is separated from a concentrated solution by a **partially permeable** membrane, water diffuses across the membrane from the dilute to the concentrated solution.



A partially permeable membrane is porous but allows water to pass through more rapidly than dissolved substances.

Since a dilute solution contains, in effect, more water molecules than a concentrated solution, there is a diffusion gradient which favors the passage of water from the dilute solution to the concentrated solution. In living cells, the cell membrane is partially permeable and the cytoplasm and vacuole (in plant cells) contain dissolved substances.

As a consequence, water tends to diffuse into cells by osmosis if they are surrounded by a weak solution, e.g. fresh water. If the cells are surrounded by a stronger solution, e.g. sea water, the cells may lose water by osmosis. These effects are described more fully later.

Animal Cells:

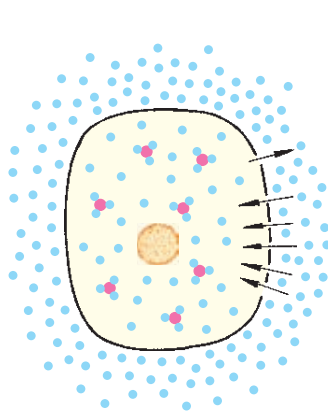
In the figure below an animal cell is shown very simply. The colored circles represent molecules in the cytoplasm. They may be sugar, salt or protein molecules. The blue circles represent water molecules.

The cell is shown surrounded by pure water. Nothing is dissolved in the water; it has 100% concentration of water molecules. So the concentration of free water molecules outside the cell is greater than that inside and, therefore, water will diffuse into the cell by osmosis.

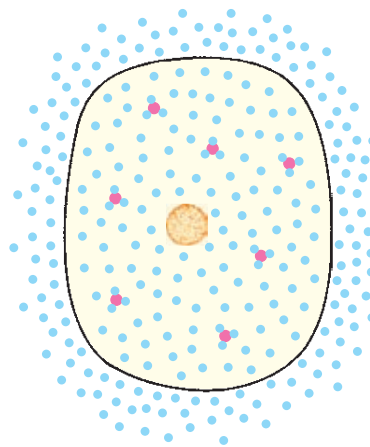
The membrane allows water to go through either way. So, in our example, water can move into or out of the cell.

The cell membrane is partially permeable to most of the substances dissolved in the cytoplasm. So, although the concentration of these substances inside may be high, they cannot diffuse freely out of the cell.

The water molecules move into and out of the cell, but because there are more of them on the outside, they will move in faster than they move out. The liquid outside the cell does not have to be 100% pure water. As long as the concentration of water outside is higher than that inside, water will diffuse in by osmosis.



(a) There is a higher concentration of free water molecules outside the cell than inside, so water diffuses into the cell.



(b) The extra water makes the cell swell up.

Water entering the cell will make it swell up and, unless the extra water is expelled in some way, the cell will burst.

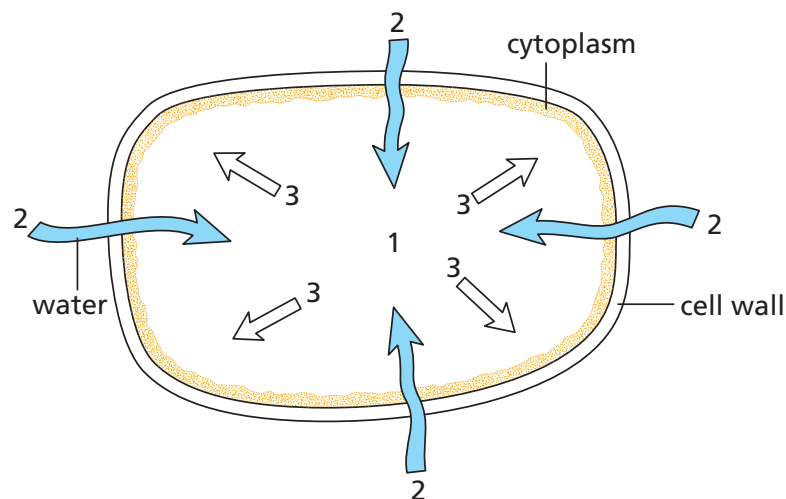
Conversely, if the cells are surrounded by a solution which is more concentrated than the cytoplasm, water will pass out of the cell by osmosis and the cell will shrink. Excessive uptake or loss of water by osmosis may damage cells.

For this reason, it is very important that the cells in an animal's body are surrounded by a liquid which has the same concentration as the liquid inside the cells. The liquid outside the cells is called **tissue fluid** and its concentration depends on the concentration of the blood. In vertebrates, the concentration of the blood is monitored by the brain and adjusted by the kidneys.

By keeping the blood concentration within narrow limits, the concentration of the tissue fluid remains more or less constant and the cells are not bloated by taking in too much water or dehydrated by losing too much.

Plant Cells:

The cytoplasm of a plant cell and the cell sap in its vacuole contain salts, sugars and proteins which effectively reduce the concentration of free water molecules inside the cell. The cell wall is freely permeable to water and dissolved substances but the cell membrane of the cytoplasm is partially permeable. If a plant cell is surrounded by water or a solution more dilute than its contents, water will pass into the vacuole by osmosis. The vacuole will expand and press outwards on the cytoplasm and cell wall. The cell wall of a mature plant cell cannot be stretched, so there comes a time when the inflow of water is resisted by the inelastic cell wall, as shown in the figure.



- 1 since there is effectively a lower concentration of water in the cell sap
- 2 water diffuses into the vacuole
- 3 and makes it push out against the cell wall

This has a similar effect to inflating a soft bicycle tire. The tire represents the firm cell wall, the floppy inner tube is like the cytoplasm and the air inside corresponds to the vacuole. If enough air is pumped in, it pushes the inner tube against the tire and makes the tire hard.

When plant cells have absorbed a maximum amount of water by osmosis, they become very rigid, due to the pressure of water pressing outwards on the cell wall. The end result is that the stems and leaves are supported. If the cells lose water there is no longer any water pressure pressing outwards against the cell walls and the stems and leaves are no longer supported. At this point, the plant becomes limp and wilts.

How Osmosis Works:

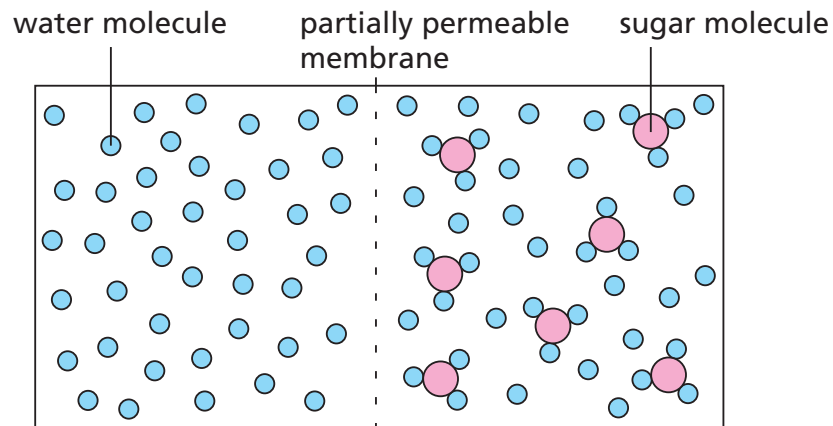
When a substance such as sugar dissolves in water, the sugar molecules attract some of the water molecules and stop them moving freely. This, in effect, reduces the concentration of water molecules. In the first figure below the sugar molecules on the right have captured half the water molecules. There are more free water molecules on the left of the membrane than on the right, so water will diffuse more rapidly from left to right across the membrane than from right to left.

The partially permeable membrane does not act like a sieve in this case. The sugar molecules can diffuse from right to left but, because they are bigger and surrounded by a cloud of water molecules, they diffuse more slowly than the water, as shown in second figure below.

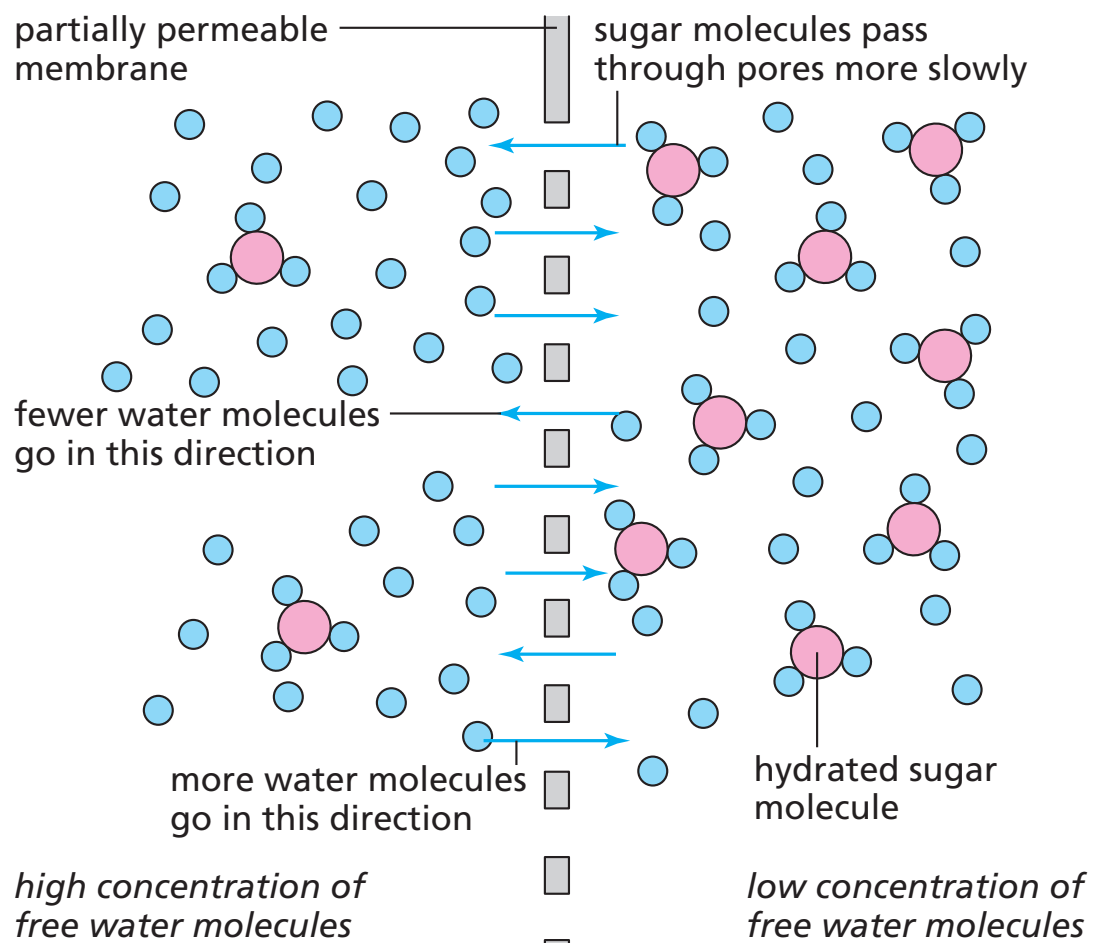
Artificial partially permeable membranes are made from cellulose acetate in sheets or tubes and used for **dialysis**. The pore size can be adjusted during manufacture so that large molecules cannot get through at all.

The **cell membrane** behaves like a partially permeable membrane. The partial permeability may depend on pores in the cell membrane but the processes involved are far more complicated than in an artificial membrane and depend on the structure of the membrane and on living processes in the cytoplasm. The cell membrane contains lipids and proteins. Anything which denatures proteins, for example, heat, also destroys the structure and the partially permeable properties of a cell membrane. If this happens, the cell will die as essential substances diffuse out of the cell and harmful chemicals diffuse in.

The diffusion gradient for water. There are more free water molecules on the left, so more will diffuse from left to right than in the other direction. Sugar molecules will diffuse more slowly from right to left.



The Diffusion Theory of Osmosis:



Water Potential:

The **water potential** of a solution is a measure of whether it is likely to lose or gain water molecules from another solution. A dilute solution, with its high proportion of free water molecules, is said to have a higher water potential than a concentrated solution, because water will flow from the dilute to the concentrated solution (from a high potential to a low potential). Pure water has the highest possible water potential because water molecules will flow from it to any other aqueous solution, no matter how dilute. When adjacent cells contain sap with different water potentials, a water potential gradient is created. Water will move from a cell with a higher water potential (a more dilute solution) to a cell with a lower water potential (a more concentrated solution). This is thought to be one way in which water moves from root hair cells through to the xylem of a plant root.

The Importance of Water Potential and Osmosis in The Uptake of Water by Plants:

A plant cell with the vacuole pushing out on the cell wall is said to be **turgid** and the vacuole is exerting **turgor pressure** on the inelastic cell wall. If all the cells in a leaf and stem are turgid, the stem will be firm and upright and the leaves held out straight. If the vacuoles lose water for any reason, the cells will lose their turgor and become **flaccid**.

If a plant has flaccid cells, the leaves will be limp and the stem will droop. A plant which loses water to this extent is said to be wilting.

Root hair cells are in contact with water trapped between soil particles. When the water potential of the cell sap is lower than that of the soil water, the water will enter the cells by osmosis providing the plant with the water it needs.

When a farmer applies chemical fertilizers to the soil, the fertilizers dissolve in the soil water. Too much fertilizer can lower the osmotic potential of the soil water. This can draw water out of the plant root hair cells by osmosis, leading to wilting and death of crop plants.

Irrigation of crops can have a similar effect. Irrigation which provides just enough water for the plant can lead to a build-up of salts in the soil. The salts will eventually cause the soil water to have a lower water potential than the plant root cells. Crops can then no longer be grown on the land, because they wilt and die because of water loss by osmosis. Much agricultural land in hot countries has become unusable due to the side-effects of irrigation.

Some countries apply salt to roads in the winter to prevent the formation of ice.

However, vehicle wheels splash the salt on to plants at the side of the road. The build-up of salts in the roadside soil can kill plants living there, due to water loss from the roots by osmosis.

The Importance of Water Potential and Osmosis in Animal Cells and Tissues:

It is vital that the fluid which bathes cells in animals, such as tissue fluid or blood plasma, has the same water potential as the cell contents. This prevents any net flow of water into or out of the cells. If the bathing fluid has a higher water potential (a weaker concentration) than the cells, water will move into the cells by osmosis causing them to swell up. As animal cells have no cell wall and the membrane has little strength, water would continue to enter and the cells will eventually burst (a process called **hemolysis** in red blood cells). Single-celled animals such as *Amoeba* living in fresh water obviously have a problem. They avoid bursting by possessing a **contractile vacuole**. This collects the water as it enters the cell and periodically releases it through the cell membrane, effectively baling the cell out. When surgeons carry out operations on a patient's internal organs, they sometimes need to rinse a wound. Pure water cannot be used as this would enter any cells it came into contact with and cause them to burst. A saline solution, with the same water potential as tissue fluid, has to be used.

Diarrhea is the loss of watery feces. It is caused when water cannot be absorbed from the contents of the large intestine, or when extra water is secreted into the large intestine due to a viral or bacterial infection. For example, the cholera bacterium produces a toxin (poison) that causes the secretion of chloride ions into the small intestine. This lowers the water potential of the gut contents, so water is drawn into the intestine by osmosis. The result is the production of watery feces. Unless the condition is treated, dehydration and loss of salts occur, which can be fatal. Patients need rehydration therapy. This involves the provision of frequent sips of water and the use of rehydration drinks. These usually come in sachets available from pharmacists and supermarkets. The contents are dissolved in water and drunk to replace the salts and glucose that are lost through dehydration.

During physical activity, the body may sweat in order to maintain a steady temperature. If liquids are not drunk to compensate for water loss through sweating, the body can become dehydrated. Loss of water from the blood results in the plasma becoming more concentrated (its water potential decreases). Water is then drawn out of the red blood cells by osmosis. The cells become **plasmolyzed**.

Their surface area is reduced, causing them to be less effective in carrying oxygen. The shape of the cells is known as being **crenated**.

People doing sport sometimes use sports drinks which are **isotonic** (they have the same water potential as body fluids). The drinks contain water, salts and glucose and are designed to replace lost water and salts, as well as providing energy, without creating osmotic problems to body cells. However, use of such drinks when not exercising vigorously can lead to weight gain in the same way as the prolonged use of any sugar rich drink.

Active Transport:

Active transport is the movement of particles through a cell membrane from a region of lower concentration to a region of higher concentration using the energy from respiration.

The Importance of Active Transport:

If diffusion were the only method by which a cell could take in substances, it would have no control over what went in or out. Anything that was more concentrated outside would diffuse into the cell whether it was harmful or not. Substances which the cell needed would diffuse out as soon as their concentration inside the cell rose above that outside it. The cell membrane, however, has a great deal of control over the substances which enter and leave the cell.

In some cases, substances are taken into or expelled from the cell against the concentration gradient. For example, sodium ions may continue to pass out of a cell even though the concentration outside is greater than inside. The cells lining the small intestine take up glucose against a concentration gradient. The processes by which substances are moved against a concentration gradient are not fully understood and may be quite different for different substances but they are all generally described as **active transport**.

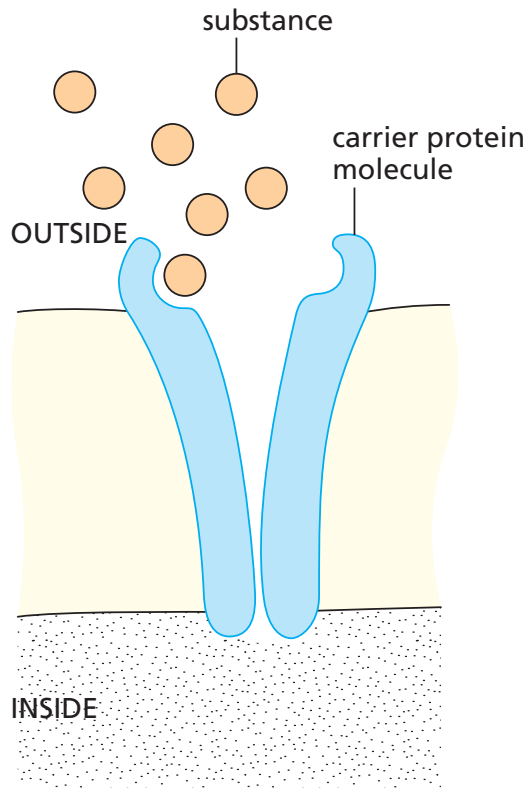
Anything which interferes with respiration, such as a lack of oxygen or glucose, prevents active transport taking place. This indicates that active transport needs a supply of energy from respiration.

The carrier molecules shown in the figure are protein molecules. As shown in (b), they are responsible for transporting substances across the membrane during active transport.

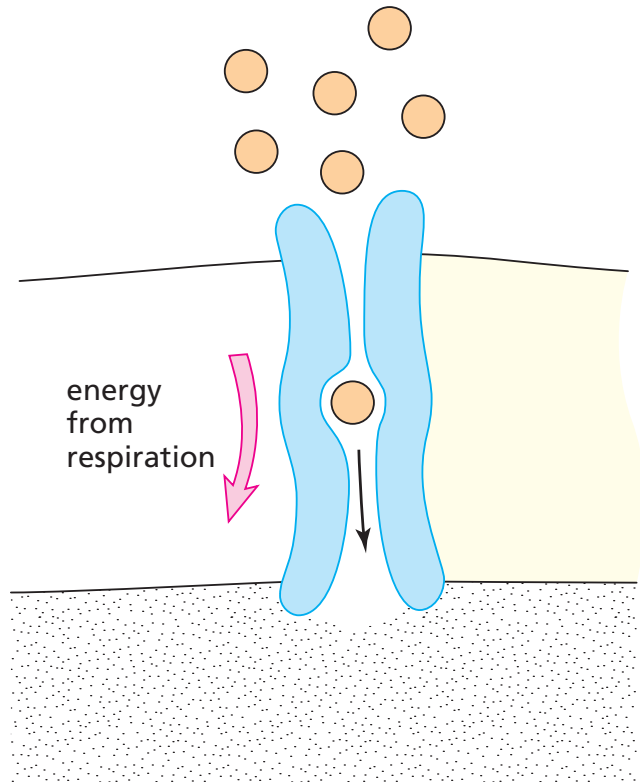
In some cases, a combination of active transport and controlled diffusion seems to occur. For example, sodium ions are thought to get into a cell by diffusion through special pores in the membrane and are expelled by a form of active transport. The reversed diffusion gradient for sodium ions created in this way is very important in the conduction of nerve impulses in nerve cells.

Epithelial cells in the villi of the small intestine have the role of absorbing glucose against a concentration gradient. The cells contain numerous mitochondria in which respiration takes place. The chemical energy produced is converted into kinetic energy for the movement of the glucose molecules. The same type of process occurs in the cells of the kidney tubules for the reabsorption of glucose molecules into the bloodstream against their concentration gradient.

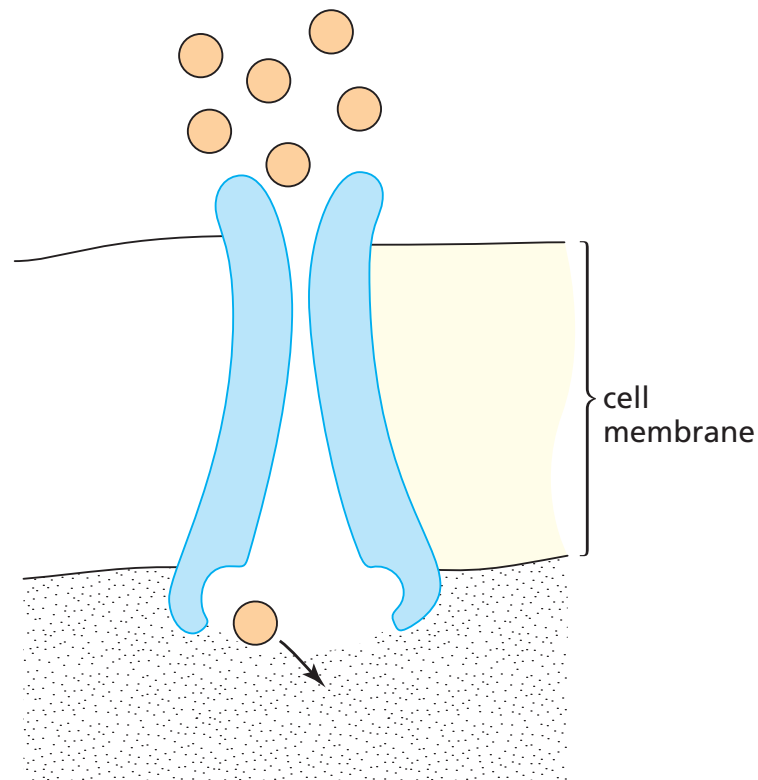
Plants need to absorb mineral salts from the soil, but these salts are in very dilute solution. Active transport enables the cells of plant roots to take up salts from this dilute solution against the concentration gradient. Again, chemical energy from respiration is converted into kinetic energy for movement of the salts.



(a) substance combines with carrier protein molecule



(b) carrier transports substance across membrane using energy from respiration



(c) substance released into cell