

01

Cells

Essential ideas

- 1.1** The evolution of multicellular organisms allowed cell specialization and cell replacement.
- 1.2** Eukaryotes have a much more complex cell structure than prokaryotes.
- 1.3** The structure of biological membranes makes them fluid and dynamic.
- 1.4** Membranes control the composition of cells by active and passive transport.
- 1.5** There is an unbroken chain of life from the first cells on Earth to all cells in organisms alive today.
- 1.6** Cell division is essential but must be controlled.

Cytology is the study of all aspects of a cell. As our understanding of the cell has increased, so has our ability to understand all forms of life, including diseases, that occur on Earth. However, there is still much work to be done in order to solve all the mysteries of the cell. Biological research laboratories all over the world are very active in this area.

Whether organisms are extremely small or extremely large, it is vital we understand their smallest functional units. These units are known as cells. Organisms range in size from a single cell to trillions of cells. To understand better all the organisms around us we must study their cells.

In this chapter, we will begin with a look at cell theory. After cell theory we will learn about the differences between prokaryotic and eukaryotic cells. A detailed explanation of cell parts and their functions will then follow. As much attention today is given to cancer, which seems to occur in most organisms and involves abnormal cell reproduction, we will focus on normal cell reproduction. Some time will also be spent on understanding how the most complex cells may have come into existence on our planet.

Look at the picture on the right. Human nerve cells (neurones) are essential to our lives. Because of these cells, we are able to acknowledge and respond to our surroundings. Neurones are usually very efficient but sometimes things go wrong. Can we gain a greater understanding and better treatment of conditions such as depression by learning more about how these cells function?

HeLa cells were the first cells to be successfully cultured on a large scale and have been used extensively in biological research, including the development of the first polio vaccine.

This is an artist's impression of human nerve cells.



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Looking for trends and discrepancies: although most organisms conform to cell theory, there are exceptions.

Ethical implications of research: research involving stem cells is growing in importance and raises ethical issues.



1.1

Cell theory, cell specialization, and cell replacement

Understandings:

- According to the cell theory, living organisms are composed of cells.
- Organisms consisting of only one cell carry out all functions of life in that cell.
- Surface area to volume ratio is important in the limitation of cell size.
- Multicellular organisms have properties that emerge from the interaction of their cellular components.
- Specialized tissues can develop by cell differentiation in multicellular organisms.
- Differentiation involves the expression of some genes and not others in a cell's genome.
- The capacity of stem cells to divide and differentiate along different pathways is necessary in embryonic development and also makes stem cells suitable for therapeutic uses.

Applications and skills:

- Application: Questioning the cell theory using atypical examples, including striated muscles, giant algae, and aseptate fungal hyphae.
- Application: Investigation of functions of life in *Paramecium* and one named photosynthetic unicellular organism.
- Application: Use of stem cells to treat Stargardt's disease and one other named condition.
- Application: Ethics of the therapeutic use of stem cells from specially created embryos, from the umbilical cord blood of a newborn baby and from an adult's own tissues.
- Skill: Use of a light microscope to investigate the structure of cells and tissues, with drawing of cells. Calculation of the magnification of drawings and the actual size of structures and ultrastructures shown in drawings or micrographs.

Guidance

- Students are expected to be able to name and briefly explain these functions of life: nutrition, metabolism, growth, response, excretion, homeostasis, and reproduction.
- *Chlorella* or *Scenedesmus* are suitable photosynthetic unicells, but *Euglena* should be avoided as it can feed heterotrophically.
- Scale bars are useful as a way of indicating actual sizes in drawings and micrographs.

Cell theory

It has taken several hundred years of research to formulate the cell theory that is used today. Many scientists have contributed to developing the three main principles of this theory. These three principles are:

- 1 all organisms are composed of one or more cells
- 2 cells are the smallest units of life
- 3 all cells come from pre-existing cells.

Cell theory has a very solid foundation largely because of the use of the microscope. Robert Hooke first described cells in 1665 after looking at cork with a self-built microscope. A few years later Antonie van Leeuwenhoek observed the first living cells and referred to them as 'animalcules', meaning little animals. In 1838, the botanist Matthias Schleiden stated that plants are made of 'independent, separate beings' called cells. One year later, Theodor Schwann made a similar statement about animals.

The second principle continues to gain support today, because so far no one has been able to find any living entity that is not made of at least one cell.

Some very famous scientists, such as Louis Pasteur in the 1880s, have performed experiments to support the third principle. After sterilizing chicken broth (soup) by

boiling it, Pasteur showed that living organisms would not 'spontaneously' reappear. Only after exposure to pre-existing cells was life able to re-establish itself in the sterilized chicken broth.

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As with most scientific theories, cell theory is not without areas of concern and problems. A key characteristic of a good scientist is a sceptical attitude towards theoretical claims. To overcome or validate this scepticism, evidence obtained by observation or experimentation is essential. Whenever possible in science, controlled experiments are needed to verify or refute theories. These experiments have a control group and a variable group(s). The groups are kept under similar conditions apart from the factor that is being tested or questioned. The factor being tested is referred to as the independent variable. The dependent factor is measured or described using quantitative or qualitative data. Relatively recent findings that have raised questions about cell theory include observations of striated muscle, giant algae, and aseptate fungal hyphae.

As this chapter develops and more information about the basic characteristics of cells is learned, some recent findings will be discussed.

Functions of life

All organisms exist in either a unicellular or a multicellular form. Interestingly, all organisms, whether unicellular or multicellular, carry out all the functions of life. These functions include:

- metabolism
- reproduction
- homeostasis
- excretion
- growth
- response
- nutrition

All of these functions act together to produce a viable living unit. Metabolism includes all the chemical reactions that occur within an organism. Cells have the ability to convert energy from one form into another. Growth may be limited but is always evident in one way or another. Reproduction involves hereditary molecules that can be passed to offspring. Responses to stimuli in the environment are imperative for the survival of an organism. These responses allow an organism to adapt to its environment. Homeostasis refers to the maintenance of a constant internal environment. For example, an organism may have to control fluctuating temperature and acid-base levels to create a constant internal environment. Providing a source of compounds with many chemical bonds that can then be broken down to provide an organism with the energy necessary to maintain life is the basis of nutrition. Excretion is essential to life because it enables those chemical compounds that an organism cannot use or that may be toxic or harmful to it to be released from the organism's system.

Two organisms can be used to demonstrate the functions of life: *Paramecium* and *Chlorella*.

Paramecium is a unicellular member of the kingdom known as the Protista. Study the diagram of a *Paramecium* to become familiar with this organism's basic structure.

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Theories are developed after the accumulation of a great deal of data via observation and/or experimentation. Sometimes theories will be abandoned completely because of conflicting evidence.

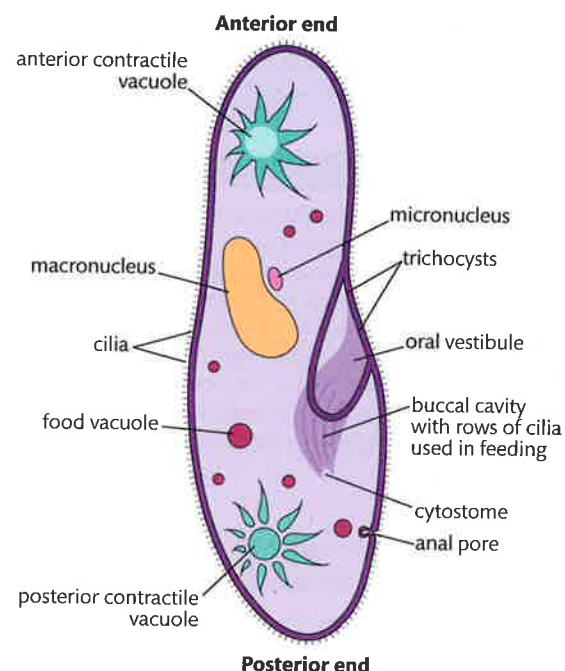


Viruses, prions, and viroids are not considered to be living organisms. They cannot carry out the functions of life on their own. However, they may use cells to perpetuate themselves.



The functions of life manifest in different ways in different types of organisms. However, all organisms maintain the same general functions that allow them to continue life. You may see different terms for these functions in other sources.

Figure 1.1 *Paramecium*. This single-celled organism may be used to demonstrate several of the functions of life.



CHALLENGE YOURSELF

Answer the following questions about the observations you made in the labs.

- 1 With the paramecia, the microorganisms should have clustered around the negative pole. Which of the processes of life is demonstrated by this action?
- 2 You should have seen that when food was added to a culture of paramecia they clustered around the food particles. Which of the functions of life does this represent?
- 3 After these organisms had used the food particles, what life function would they carry out to get rid of potentially toxic wastes?
- 4 Two of the structures shown in the diagram of a *Paramecium* (Figure 1.1) are involved in excretion or internal water concentration regulation. They are the anal pore and the contractile vacuole. Conduct some research into the role each of these structures plays in excretion.



Paramecium and the functions of life

Safety alerts: Be cautious of sharp objects. Only use a 9-volt battery as an electrical source. Make sure your instructor checks your set-up before you begin. Wash your hands thoroughly with soap and water before and after the procedure.

Paramecium can be used to demonstrate the functions of life in several ways.

- 1 Place a number of paramecia into a Syracuse dish or an evaporating dish with positive and negative electrodes of low-voltage electrical charge on opposite sides. A simple 9-volt battery will usually trigger a response. Do not use electricity of a higher voltage, otherwise the organism will be harmed. Low-voltage electricity can be applied for several minutes. The dish should be placed on the stage of a dissecting microscope. A strong magnifying lens may also be used. Describe the movement and final location of the largest population of paramecia.
- 2 Once this activity has ended, remove the electrodes and add several small, but visible, pieces of hard-boiled egg yolk. Again, using the magnifying instrument make observations of the movement and final location of the paramecia.
- 3 Finally, to a culture of paramecia add a drop of very dilute acetic acid (vinegar). Once again, report on the movement and final location of the paramecia.
- 4 When you have finished these tests, your teacher will explain what should be done with the organisms. Respect for life is very important in our studies. The IB policy on animal experimentation must be followed at all times.
- 5 Using what you know about the functions of life, explain why the paramecia moved in the ways you observed.

The next organism we will look at is *Chlorella*. Compared with *Paramecium*, *Chlorella* has a completely different approach to nutrition. *Chlorella* is a single-celled organism that has one very large structure called a chloroplast inside a cell wall. This structure enables the conversion of the energy in sunlight to a chemical energy form called carbohydrate. This carbohydrate provides the major nutritional source for the organism. Study the diagram of a *Chlorella*.

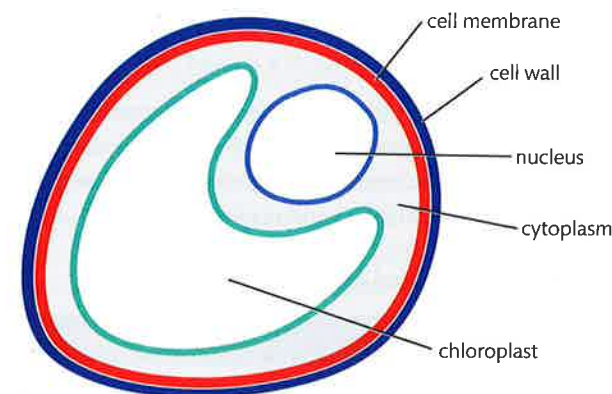


Figure 1.2 *Chlorella*. A common freshwater organism. This organism has been used by many researchers to determine the details of, and the factors that affect, a process known as photosynthesis. The structure labelled chloroplast is especially important in this process.

Chlorella and the functions of life

Safety alerts: Be cautious of sharp objects. Follow classroom rules for use of microscope. Wash your hands thoroughly with soap and water before and after the procedure.

Many classroom practical activities can be carried out with cultures of *Chlorella*. Carry out the following activity.

- 1 Obtain two depression microscope slides, and place the same number of *Chlorella* organisms in a proper culture medium in each well.
- 2 Seal a cover slip on each slide with a ring of petroleum jelly.
- 3 To reduce evaporation further, place each slide in a Petri dish.
- 4 Place one Petri dish with its slide in sunlight.
- 5 Place the other Petri dish in complete darkness.
- 6 Using a microscope, check the numbers of *Chlorella* on each slide for 3 days.
- 7 Use the functions of life to explain the results observed.
- 8 An advanced activity can be carried out. Using a culture of *Chlorella*, design an experiment that would allow you to see what colour (wavelength) of light this organism prefers.

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Perhaps in the design of the *Chlorella* activity you had an idea based on your previous experiences in science about what the outcome of your procedure would be. This idea is referred to as a hypothesis. Scientists form hypotheses that can be tested by observation and/or experimentation. These tested hypotheses may ultimately serve to simplify and unify existing scientific ideas.

Controlled experiments are the best way to investigate the relationship between two factors or variables. However, this type of experiment is not always possible. In this case, statistical analysis of the data may indicate a correlation. As time and research proceeds, a causal relationship may be seen. Objective data, both qualitative and quantitative, are used to establish relationships whenever possible. It is essential that repeated measurements are taken and that large numbers of readings are taken so that the data collection is reliable. Scientists spend a lot of time working with people from other disciplines in order to gain a greater understanding of their findings. They also read current scientific articles throughout their career in order to gain further insight into their research. Eventually, a researcher may decide to publish his or her findings in an appropriate scientific journal. For this to happen, an article undergoes a peer-review process, which means several scientists working in the same field read the article before it is published to make sure the methodologies and findings are sound and honest.

Cells and sizes

Cells are made up of a number of different subunits. These subunits are often of a particular size, but all are microscopically small. In most cases the use of microscopes



Correlation and cause are extremely important in scientific research. A correlation means there is a statistical link relating one variable or factor with another. In the case of a causal relationship, one factor causes another; there must be a scientific process or mechanism connecting the factors with one another.



Most cells can be up to 100 micrometres (μm) in size. Organelles can be up to 10 μm in size. Bacteria can be up to 1 μm in size. Viruses can be up to 100 nanometres (nm) in size. Cell membranes are 10 nm thick, while molecules are about 1 nm in size. All of these objects are three-dimensional.

with a high magnification and resolution are needed to observe cells and especially their subunits. Resolution refers to the clarity of a viewed object.

Light microscopes use light, passing through living or dead specimens, to form an image. Stains may be used to make it easier to see any details. Electron microscopes use electrons passing through a dead specimen to form an image and provide us with the greatest magnifications (over 100 000 \times) and resolution.

Table 1.1 A comparison of light and electron microscopes

Light microscope	Electron microscope
Inexpensive to purchase and operate	Expensive to purchase and operate
Simple and easy specimen preparation	Complex and lengthy specimen preparation
Magnifies up to 2000 \times	Magnifies over 500 000 \times
Specimens may be living or dead	Specimens are dead, and must be fixed in a plastic material

Cells and their subunits are so small they are hard to visualize, so it is important to appreciate their relative sizes. Cells are relatively large, and then in decreasing order of size are:

- organelles
- bacteria
- viruses
- membranes
- molecules.

If you want to calculate the actual size of a specimen seen with a microscope, you need to know the diameter of the microscope's field of vision. This can be calculated with a special micrometre, or on a light microscope with a simple ruler. The size of the specimen can then be worked out. Drawings or photographs of specimens are often enlarged. To calculate the magnification of a drawing or photograph, a simple formula is used:

$$\text{magnification} = \text{size of image} / \text{size of specimen.}$$

Scale bars are often used with a micrograph or drawing so that the actual size can be determined. Scale bars and magnification will be addressed in more detail in a later practical activity.

Worked example

The length of an image you are looking at is 50 mm. If the actual length of the subject of the image is 5 μm , what is the magnification of the image you are looking at?

Solution

$$\text{magnification} = 50 \text{ mm} / 5 \mu\text{m} = 50\,000 \mu\text{m} / 5 \mu\text{m} = 10\,000\times$$

$$\text{Or: magnification} = 50 \text{ mm} / 5 \mu\text{m} = 50 \times 10^{-3} \text{ m} \text{ divided by } 1 \times 10^{-6} \text{ m} = 10\,000\times$$

Limiting cell size

So, the cell is a small object. You may wonder why cells do not grow to larger sizes, especially as growth is one of the functions of life. There is a principle called the surface area to volume ratio that effectively limits the size of cells. In a cell, the rate of heat and waste production, and rate of resource consumption, are functions of (depend on) its volume. Most of the chemical reactions of life occur inside a cell, and the size of the cell affects the rate of those reactions. The surface of the cell, the membrane, controls what materials move in and out of the cell. A cell with more surface area per unit volume is able to move more materials in and out of the cell, for each unit volume of the cell.

As the width of an object such as a cell increases, the surface area also increases, but at a much slower rate than the volume. This is shown in the following table: the volume increases by a factor calculated by cubing the radius; at the same time, the surface area increases by a factor calculated by squaring the radius.

Table 1.2 Surface area to volume ratios

Factor	Measurement		
Cell radius (r)	0.25	0.50	1.25
Surface area	0.79	3.14	19.63
Volume	0.07	0.52	8.18
Surface area : volume ratio	11.29 : 1	6.04 : 1	2.40 : 1

This means that a large cell, compared with a small cell, has relatively less surface area to bring in materials that are needed and to get rid of waste. Because of this, cells are limited in the size they can reach and still be able to carry out the functions of life. Thus large animals do not have larger cells; instead they have more cells.

Cells that are larger in size have modifications that allow them to function efficiently. This is accomplished with changes in shape, such as being long and thin rather than spherical. Some larger cells also have infoldings or outfoldings to increase their surface area relative to their volume.

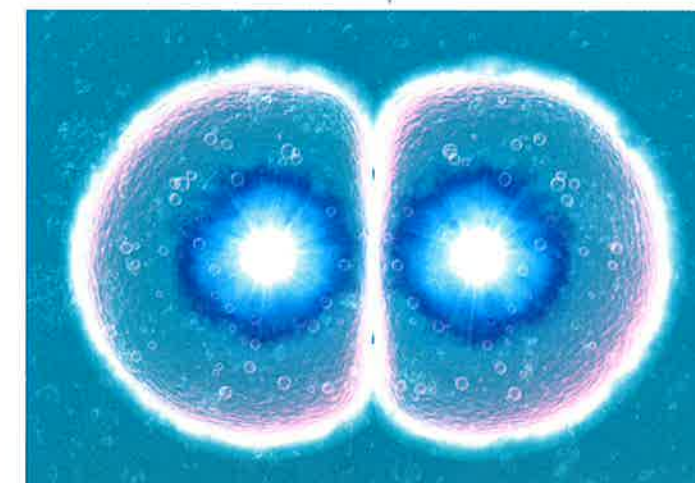
Cell reproduction and differentiation

One of the functions that many cells have is the ability to reproduce themselves. In multicellular organisms this allows growth to happen. It also means damaged or dead cells can be replaced.

Multicellular organisms usually start their existence as a single cell after some type of sexual reproduction. This single cell has the ability to reproduce at a very rapid rate, and the resulting cells then go through a differentiation process to produce all the required cell types that are necessary for the well-being of the organism. The number of different cell types that can arise from the one original cell can be staggering. This differentiation process is the result of the expression of certain specific genes but not

Sphere formulas:
Surface area = (four)(pi)(radius squared)
Volume = (four-thirds)(pi)(radius cubed)

This is a computer artwork of an egg cell fertilized during *in vitro* fertilization and now undergoing the first cell division.



Cancer cells are examples of cells that undergo extremely rapid reproduction with very little or improper differentiation. The result is a mass of cells (a tumour) with no useful function to the organism.

When discussing the overall functions of a cell, you should focus on the distinctions between living and non-living factors in the environment. It is very useful and productive to refer to the functions of life in such a discussion.

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others. Genes, segments of DNA on a chromosome, enable the production of all the different cells in an organism. Therefore, each cell contains all the genetic information needed for the production of the complete organism. However, each cell will become a specific type of cell depending on which DNA segment becomes active.

Some cells have a greatly reduced ability to reproduce once they become specialized, or lose the ability altogether. Nerve and muscle cells are good examples of this type of cell. Other cells, including epithelial cells such as skin, retain the ability to reproduce rapidly throughout their life. The offspring of these rapidly reproducing cells will then differentiate into the same cell type as the parent.

One of the results of cell reproduction and the subsequent differentiation process that occurs in multicellular organisms is emergent properties. These properties depend on the interactions between all the different parts of a particular biological unit, such as the cell. When you look at the function(s) of each part of a cell, it is less than the overall function of the complete cell. In other words, the whole is more than the sum of its parts. To continue with this emergent concept, a whole multicellular organism is capable of carrying out more functions than the sum of the function(s) each cell is specialized in. The ultimate example of emergence is a collection of inert (non-living) molecules that is capable, when functioning together, of creating a living entity that demonstrates the functions of life.

Stem cells

There are populations of cells within organisms that retain their ability to divide and differentiate into various cell types. These cells are called stem cells.

Plants contain such cells in regions of meristematic tissue. Meristematic tissues occur near root and stem tips and are composed of rapidly reproducing cells that produce new cells capable of becoming various types of tissue within that root or stem.

Gardeners take advantage of these cells when they take cuttings from stems or roots and use them to propagate new plants.

In the early 1980s, scientists found pluripotent or embryonic stem cells in mice. These stem cells retain the ability to form any type of cell in an organism and can even form a complete organism.

When stem cells divide to form a specific type of tissue, they also produce some daughter cells that stay as stem cells. This enables the continual production of a particular type of tissue. Medical scientists saw the possibilities of using such cells to treat certain human diseases. However, one problem discovered early on in stem cell research was that stem cells cannot be distinguished by their appearance. They can only be isolated from other cells on the basis of their behaviour.

Stem cell research and treatments

Recently some very promising research has been directed towards growing large numbers of embryonic stem cells in culture so that they can be used to replace differentiated cells lost as a result of injury and disease. This involves therapeutic cloning. Parkinson's and Alzheimer's diseases are caused by the loss of proper functioning brain cells, and it is hoped that implanted stem cells could replace many of these lost or defective brain cells, thus relieving the symptoms of the disease. With some forms of diabetes, the pancreas is depleted of essential cells and it is hoped that

a stem cell implant in this organ could have positive effects. As at present most of the research on stem cells is being carried out using mice, it will probably be some time before this approach to treatment becomes widespread in humans.

Stem cells are being utilized in a number of ways by scientists around the world. One area of research involves using human embryonic stem cells in order to understand human development better. This research involves studies of cell division and differentiation. Other scientists are using stem cells to test the safety and effects of new drugs. Information in this area is essential to the understanding of how these drugs might affect differentiating cells in existing organisms. Another very interesting area of study involves cell-based therapies, especially as they may have a positive influence on the treatment of diseases and traumas such as Alzheimer's disease, spinal cord injuries, heart disease, diabetes, burns, and strokes.

However, there is a type of stem cell treatment that has been used successfully in humans for many years. As well as pluripotent stem cells, there are tissue-specific stem cells. These stem cells reside in certain tissue types and can only produce new cells of that particular tissue. For example, blood stem cells have been introduced routinely into humans to replace the damaged bone marrow of some leukaemia patients.

Stargardt's disease is an example of a human condition that is in the early stages of being treated with stem cells. Stargardt's disease is an inherited disease caused by both parents passing on a gene to their offspring that codes for a defect in the processing of vitamin A. Vitamin A is essential for the light-sensitive cells in the retina to function properly. With Stargardt's disease, within the first 20 years of a patient's life he or she begins to lose his or her central vision. Later on, peripheral vision loss occurs, which eventually leads to blindness.

In March 2010, a stem cell treatment was begun that was designed to protect and regenerate photoreceptors in the retina that are damaged by Stargardt's disease. Currently the particular stem cells being used for this treatment in humans are human embryonic stem cells. The study is ongoing, but the early results are promising.

There are ethical issues involved in stem cell research. The use of pluripotent stem cells is particularly controversial. These cells are obtained from embryos, largely from laboratories carrying out *in vitro* fertilization (IVF). Harvesting these cells involves the death of an embryo, and some people argue that this is taking a human life. Others argue that this research could result in a significant reduction in human suffering, and is, therefore, totally acceptable.

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How the scientific community conveys information concerning its research to the wider society is very important. The information must be accurate, complete, and understandable, so that society can make informed decisions regarding the appropriateness of the research. There is a need to balance the very great opportunities of this type of research with the potential risks. Recently, there has been evidence that some types of cancer may be caused by stem cells undergoing a cancer-like or malignant transformation. Where do you stand in the debate about the nature of stem cell research? How do you feel about the source of pluripotent stem cells?

Exercises

- 1 How is the excretion of metabolic wastes from cells related to the concept of the surface area to volume ratio?
- 2 Explain how the function of life known as nutrition differs in *Paramecium* compared with the green alga *Chlorella*.
- 3 How does specialization in muscle and nerve cells affect their ability to reproduce?
- 4 What would prevent stem cells from other species being successful in humans?

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In 2005, stem cells were used successfully to help restore the lost insulation of nerve cells in rats, thus resulting in greater mobility in these animals.



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There has been much sharing of data involving stem cell research. However, many nations have banned or restricted research in this area because of local cultural and religious traditions.

NATURE OF SCIENCE

Developments in scientific research follow improvements in apparatus: the invention of electron microscopes led to greater understanding of cell structure.



1.2 The ultrastructure of cells

Understandings:

- Prokaryotes have a simple cell structure without compartmentalization.
- Eukaryotes have a compartmentalized cell structure.
- Electron microscopes have a much higher magnification than light microscopes.

Applications and skills:

- Application: Structure and function of organelles within exocrine gland cells of the pancreas and within palisade mesophyll cells of the leaf.
- Application: Prokaryotes divide by binary fission.
- Skill: Drawing of the ultrastructure of prokaryotic cells based on electron micrographs.
- Skill: Drawing of the ultrastructure of eukaryotic cells based on electron micrographs.
- Skill: Interpretation of electron micrographs to identify organelles and deduce the function of specialized cells.

Guidance

- Drawings of prokaryotic cells should show the cell wall, pili, and flagella, and plasma membrane enclosing cytoplasm that contains 70S ribosomes and a nucleoid with naked DNA.
- Drawings of eukaryotic cells should show a plasma membrane enclosing cytoplasm that contains 80S ribosomes and a nucleus, mitochondria and other membrane-bound organelles are present in the cytoplasm. Some eukaryotic cells have a cell wall.

What is a prokaryotic cell?

After extensive studies of cells, it has become apparent that all cells use some common molecular mechanisms. There are huge differences between different forms of life but cells are the basic unit and different cells have many characteristics in common. Cells are often divided into particular groups based on major characteristics. One such division separates cells into two groups: prokaryotic and eukaryotic cells. Prokaryotic cells are much smaller and simpler than eukaryotic cells. In fact, most prokaryotic cells are less than 1 μm in diameter. Because of this, and many other reasons that will be discussed later, the prokaryotic cells are thought to have appeared on Earth first. As bacteria are prokaryotic cells, you can see that such cells play a large role in the world today.

Features of prokaryotic cells

Study the figure of a prokaryotic cell (Figure 1.3) and make sure you can identify:

- the cell wall
- the plasma membrane
- flagella
- pili
- ribosomes
- the nucleoid (a region containing free DNA).

Becoming familiar with common prefixes, suffixes and word roots will help you understand biological terms. For example, the word prokaryotic comes from the Greek word 'pro', which means 'before', and 'karyon', which means kernel, referring to the nucleus.

Bacteria and members of a group referred to as Archaea are made up of prokaryotic cells and are called prokaryotes. The vast majority of these organisms do not cause disease and are not pathogenic (disease-causing).

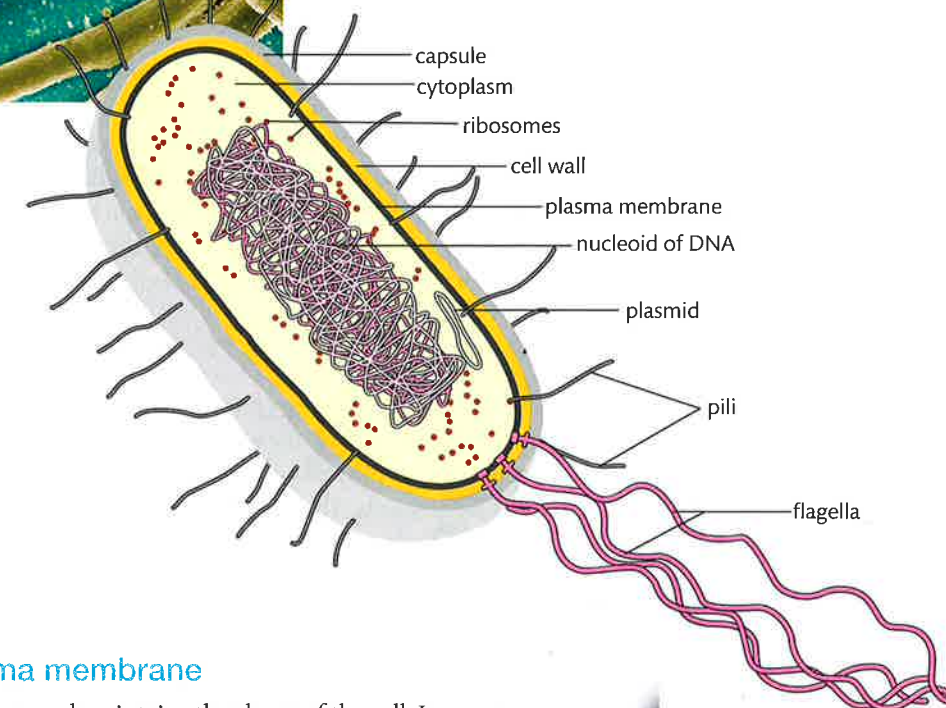
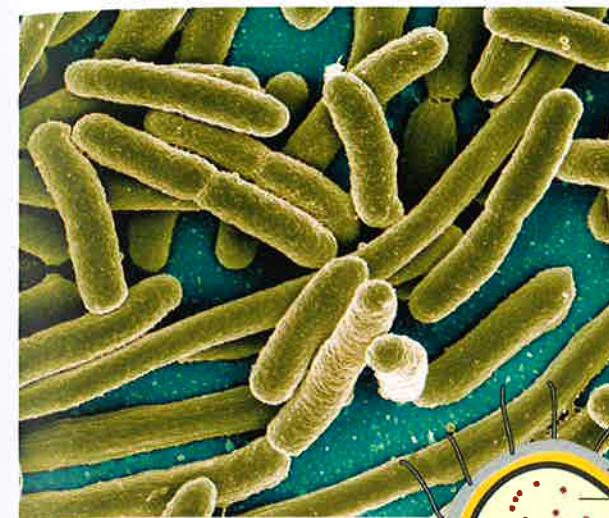


Figure 1.3 This is a false-colour scanning electron micrograph (SEM) of the bacterium *Escherichia coli*. Below is a drawing of a prokaryotic cell.

The cell wall and plasma membrane

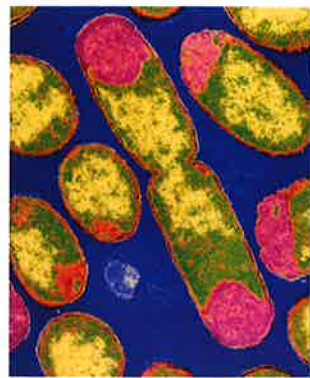
The prokaryotic cell wall protects and maintains the shape of the cell. In most prokaryotic cells this wall is composed of a carbohydrate-protein complex called peptidoglycan. Some bacteria have an additional layer of a type of polysaccharide outside the cell wall. This layer makes it possible for some bacteria to adhere to structures such as teeth, skin and food.

The plasma membrane is found just inside the cell wall and is similar in composition to the membranes of eukaryotic cells. To a large extent the plasma membrane controls the movement of materials into and out of the cell, and it plays a role in binary fission of the prokaryotic cell. The cytoplasm occupies the complete interior of the cell. The most visible structure with a microscope capable of high magnification is the chromosome or a molecule of DNA. There is no compartmentalization within the cytoplasm because there are no internal membranes other than the plasma membrane. Therefore, all cellular processes within prokaryotic cells occur within the cytoplasm.

Pili and flagella

Some bacterial cells contain hair-like growths on the outside of the cell wall. These structures are called pili and can be used for attachment. However, their main function

If there is no compartmentalization within prokaryotic cells, chemical reactions are not isolated from one another. This may limit the cell's development and efficiency because of possible interference between the reactions.



This is a false-colour transmission electron micrograph (TEM) showing *Escherichia coli* dividing by binary fission.

The importance of plasmids in prokaryotic cells will be discussed fully in Chapter 3. Plasmids have very important roles to play in some techniques involving genetic engineering/modification.

Some types of bacteria go through binary fission every 20 minutes when conditions are ideal. This results in huge populations and greater potential for infections. Refrigeration of foods is often used to reduce ideal conditions for bacteria. This results in lower bacterial counts in our food and less chance of infection/food poisoning.

CHALLENGE YOURSELF

- 5 Prepare a drawing of the ultrastructure of a prokaryotic cell based on electron micrographs. Make sure you follow the guidelines given for drawings.

is joining bacterial cells in preparation for the transfer of DNA from one cell to another (sexual reproduction).

Some bacteria have flagella (plural) or a flagellum (singular), which are longer than pili. Flagella allow a cell to move.

Ribosomes

Ribosomes occur in all prokaryotic cells and they function as sites of protein synthesis. These small structures occur in very large numbers in cells that produce a lot of protein, and, when numerous, they give a granular appearance to an electron micrograph of a prokaryotic cell.

The nucleoid region

The nucleoid region of a bacterial cell is non-compartmentalized and contains a single, long, continuous, circular thread of DNA, the bacterial chromosome. Therefore this region is involved with cell control and reproduction. In addition to the bacterial chromosome, bacteria may also contain plasmids. These small, circular, DNA molecules are not connected to the main bacterial chromosome. The plasmids replicate independently of the chromosomal DNA. Plasmid DNA is not required by the cell under normal conditions but it may help the cell adapt to unusual circumstances.

Binary fission

Prokaryotic cells divide by a very simple process called binary fission. During this process, the DNA is copied, the two daughter chromosomes become attached to different regions on the plasma membrane, and the cell divides into two genetically identical daughter cells. This divisional process includes an elongation of the cell and a partitioning of the newly produced DNA by microtubule-like fibres called FtsZ.



Very often in IB, laboratory tests and examinations will require you to draw an object or organism. Follow the guidelines given below when completing any drawing.

- The size should be appropriate for the complexity of the drawing.
- Correct positioning of structures is essential.
- The outline of structures should be continuous unless gaps or pores are present in the actual border or structure.
- Proportions are important.
- The relative numbers of parts are important.
- Draw in pencil first so that mistakes can be corrected. Write on or label the final drawing in black ink.
- Labelling must be included on all drawings unless the question tells you not to.
- Lines from labels to parts on a drawing should be straight and should never cross.
- In IB exams, boxes are provided for drawings. Do not draw or write outside the box as this area will not be scanned or marked.

Summary

Here is a list of the major distinguishing characteristics of prokaryotic cells.

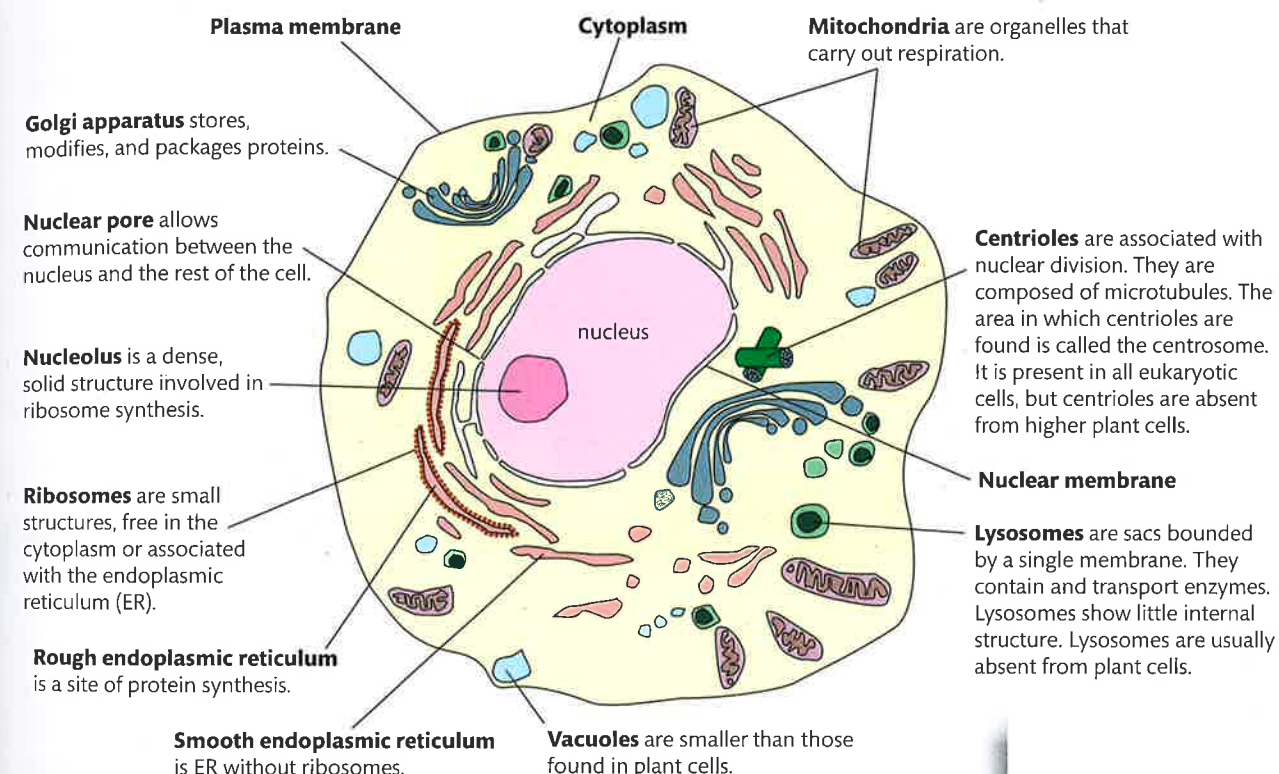
- Their DNA is not enclosed within a membrane and forms one circular chromosome.
- Their DNA is free; it is not attached to proteins.
- They lack membrane-bound organelles. Ribosomes are complex structures within the plasma membrane, but they have no exterior membrane.

- Their cell wall is made up of a compound called peptidoglycan.
- They usually divide by binary fission, a simple form of cell division.
- They are characteristically small in size, usually between 1 and 10 μm .

What is a eukaryotic cell?

Whereas prokaryotic cells occur in bacteria, eukaryotic cells occur in organisms such as algae, protozoa, fungi, plants, and animals. Examine the following diagrams and pictures.

Figure 1.4 Look at this drawing of a typical animal cell and compare it with Figure 1.5.



Eukaryotic cells range in diameter from 5 to 100 μm . A 'kernel' or nucleus is usually noticeable in the cytoplasm. Other organelles may be visible within the cell if you have a microscope with a high enough magnification and resolution. Organelles are non-cellular structures that carry out specific functions (a bit like organs in multicellular organisms); different types of cell often have different organelles. These structures enable compartmentalization in eukaryotic cells, which is not a characteristic of prokaryotic cells. Compartmentalization enables different chemical reactions to be separated, which is especially important when adjacent chemical reactions are incompatible. Compartmentalization also allows chemicals for specific reactions to be isolated; this isolation results in increased efficiency.

The term 'eukaryote' comes from the Greek word 'eukaryon' meaning true kernel or true nucleus.



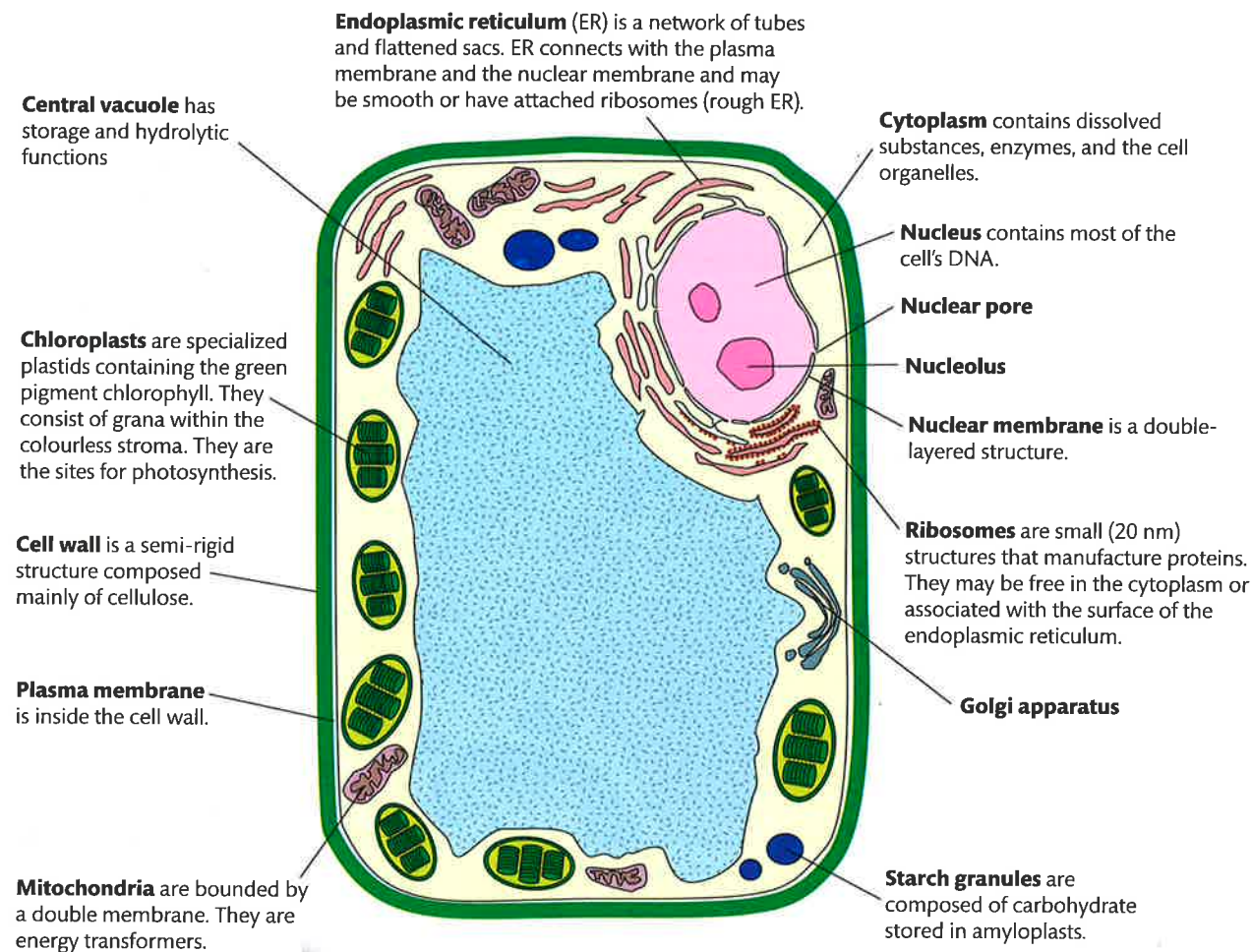
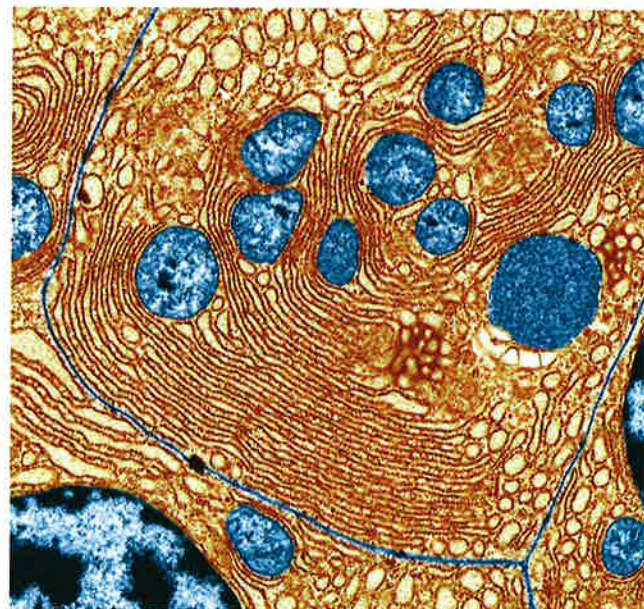


Figure 1.5 What is different and what is similar between this typical plant cell and Figure 1.4?

A TEM of a pancreatic exocrine cell. Can you tell this is an animal cell? Locate as many of the structures of an animal cell as you can. How do the structures of this cell reflect the overall functions of the pancreas?



A TEM of a cell from the mesophyll region of a leaf. How do you know this is a plant cell? Locate as many of the structures of a plant cell as you can. What cell structures reflect most the unique abilities of a plant cell?

As you read about the organelles of eukaryotic cells below, refer back to the figures above and on page 16 and add more names of organelles. Also, be certain to note which organelles are common to both types of cells and which organelles occur in only one of the two types.

Organelles of eukaryotic cells

Common organelles include the following (see Figures 1.4 and 1.5):

- endoplasmic reticulum
- ribosomes
- lysosomes (not usually found in plant cells)
- Golgi apparatus
- mitochondria
- nucleus
- chloroplasts (only in plant and algal cells)
- centrosomes (in all eukaryotic cells, but centrioles are not found in some plant cells)
- vacuoles.

The microscope has given us an insight into the structure and function of the following eukaryotic cell organelles and characteristics.

Cytoplasm

All eukaryotic cells have a region called the cytoplasm that occurs inside the plasma membrane or the outer boundary of the cell. It is in this region that the organelles are found. The fluid portion of the cytoplasm around the organelles is called the cytosol.

Endoplasmic reticulum

The endoplasmic reticulum (ER) is an extensive network of tubules or channels that extends most everywhere in the cell, from the nucleus to the plasma membrane. Its structure enables its function, which is the transportation of materials throughout the internal region of the cell. There are two general types of ER: smooth ER and rough ER. Smooth ER does not have any of the organelles called ribosomes on its exterior surface. Rough ER has ribosomes on its exterior.

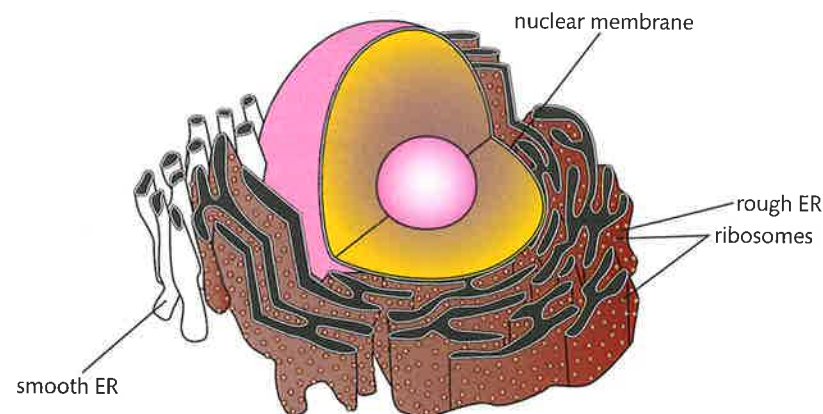


Microscopes have a rich history of international development. Glass lenses were used in the first century by the Romans to magnify objects. Salvino D'Armato, an Italian, made an eye glass in the 13th century that allowed magnification for one eye. Two Dutch eyeglass makers, Hans Jansen and his son Zacharias Jansen, in the 1590s, produced the first compound microscope by putting two lenses together. Anton van Leeuwenhoek, also Dutch, greatly improved the Jansen compound microscope in the 1600s. Since this beginning, many individuals in many different countries of the world have worked to make the present-day microscope extremely effective in the study of the cell and other small structures. Modern technology allowing extensive communication has been extremely important in the continual improvement of the present-day microscope.



Visual illusions are the result of sensory-derived images that differ from objective reality. M. C. Escher's *Waterfall* is a prime example of an optical illusion. In his print water seems to flow downhill on its way to the 'top' of the waterfall. How can the repeating of experiments in science decrease the chances of an illusion? Do you feel modern technology is decreasing the chances of these visual illusions occurring in modern-day science research?

Figure 1.6 Smooth ER and rough ER.



Smooth ER has many unique enzymes embedded on its surface. Its functions are:

- the production of membrane phospholipids and cellular lipids
- the production of sex hormones such as testosterone and oestrogen
- detoxification of drugs in the liver
- the storage of calcium ions in muscle cells, needed for contraction of muscle cells
- transportation of lipid-based compounds
- helping the liver release glucose into the bloodstream when needed.

Rough ER has ribosomes on the exterior of the channels. These ribosomes are involved in protein synthesis. Therefore, this type of ER is involved in protein development and transport. These proteins may become parts of membranes, enzymes, or even messengers between cells. Most cells contain both types of ER, with the rough ER being closer to the nuclear membrane.

Ribosomes

Ribosomes are unique structures that do not have an exterior membrane. They carry out protein synthesis within the cell. These structures may be found free in the cytoplasm or they may be attached to the surface of ER. They are always composed of a type of RNA and protein. You will recall that prokaryotic cells also contain ribosomes. However, the ribosomes of eukaryotic cells are larger and denser than those of prokaryotic cells. Ribosomes are composed of two subunits. These subunits together equal 80S. The ribosomes in prokaryotic cells are also composed of two subunits, but they only equal 70S.

Lysosomes

Lysosomes are intracellular digestive centres that arise from the Golgi apparatus. A lysosome does not have any internal structures. Lysosomes are sacs bounded by a single membrane that contain as many as 40 different enzymes. The enzymes are all hydrolytic and catalyse the breakdown of proteins, nucleic acids, lipids, and carbohydrates. Lysosomes fuse with old or damaged organelles from within the cell to break them down, so that recycling of the components can occur. Lysosomes are also involved in the breakdown of materials that may be brought into a cell by phagocytosis. Phagocytosis is a type of endocytosis that is explained on page 36 in Section 1.4. The interior environment of a functioning lysosome is acidic; this acidic environment is necessary for the enzymes to hydrolyse large molecules.

Golgi apparatus

The Golgi apparatus consists of what appears to be flattened sacs called cisternae, which are stacked one on top of another. This organelle functions in the collection, packaging, modification, and distribution of materials synthesized in the cell. One side of the apparatus is near the rough ER, called the *cis* side. It receives products from the ER. These products then move into the cisternae of the Golgi apparatus. They continue to move to the discharging or opposite side, the *trans* side. Small sacs called vesicles can then be seen coming off the *trans* side.

These vesicles carry modified materials to wherever they are needed inside or outside the cell. This organelle is especially prevalent in glandular cells, such as those in the pancreas, which manufacture and secrete substances.

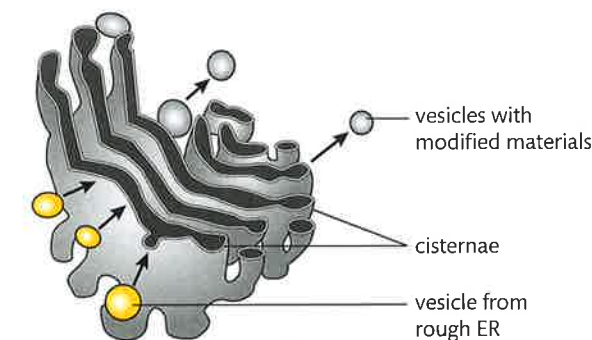


Figure 1.7 In this drawing of the Golgi apparatus, the movement of the vesicles is shown by arrows. Can you identify which side is the *cis* side and which is the *trans* side?

Mitochondria

Mitochondria (singular mitochondrion) are rod-shaped organelles that appear throughout the cytoplasm. They are close in size to a bacterial cell. Mitochondria have their own DNA, a circular chromosome similar to that in bacterial cells, allowing them some independence within a cell. They have a double membrane: the outer membrane is smooth, but the inner membrane is folded into cristae (singular crista). Inside the inner membrane is a semi-fluid substance called the matrix. An area called the inner membrane space lies between the two membranes. The cristae provide a huge surface area within which the chemical reactions characteristic of the mitochondria occur. Most mitochondrial reactions involve the production of usable cellular energy called adenosine triphosphate (ATP). Because of this, the mitochondria are often called the powerhouse of a cell. This organelle also produces and contains its own ribosomes; these ribosomes are of the 70S type. Cells that have high energy requirements, such as muscle cells, have large numbers of mitochondria.

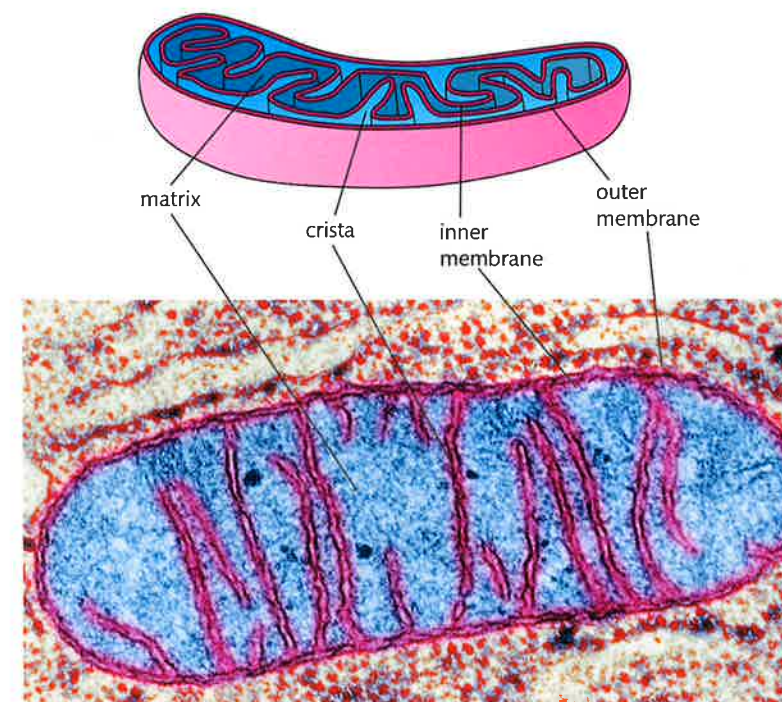


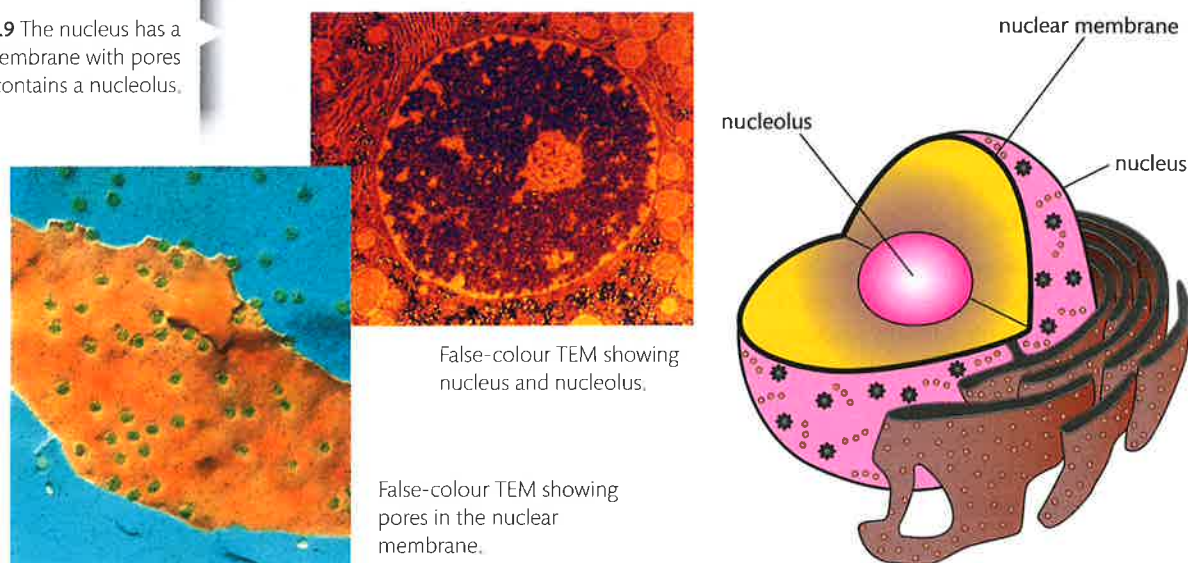
Figure 1.8 Compare this drawing of a mitochondrion with the false-colour TEM of a mitochondrion.

The letter S used in the measurement of ribosomes refers to Svedberg units, which indicate the relative rate of sedimentation during high-speed centrifugation. The higher the S value, the quicker the structure will become part of the sediment and the more mass it will have.

Nucleus

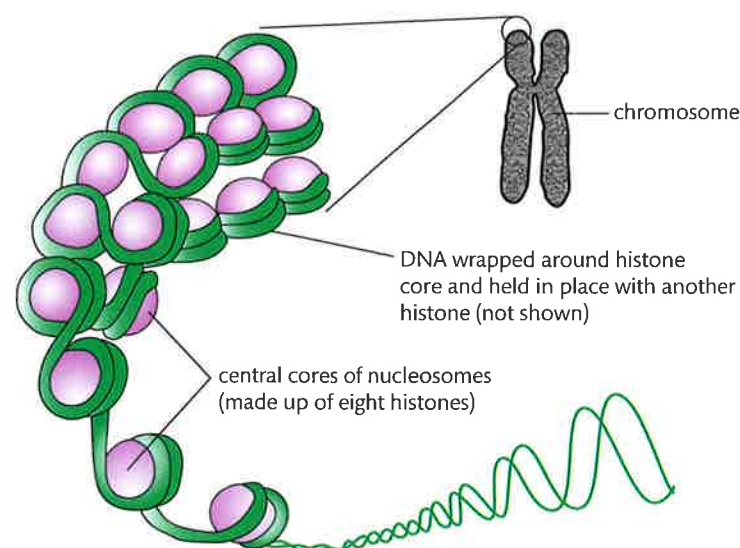
The nucleus in eukaryotic cells is an isolated region where the DNA resides. It is bordered by a double membrane referred to as the nuclear envelope. This membrane allows compartmentalization of the eukaryotic DNA, thus providing an area where DNA can carry out its functions without being affected by processes occurring in other parts of the cell. The nuclear membrane does not provide complete isolation because it has numerous pores that allow communication with the cell's cytoplasm.

Figure 1.9 The nucleus has a double membrane with pores and contains a nucleolus.



The DNA of a eukaryotic cell often occurs in the form of chromosomes; chromosomes vary in number depending on the species. Chromosomes carry all the information that is necessary for the cell to exist; this allows an organism to survive, whether it is unicellular or multicellular. The DNA is the genetic material of the cell. It enables certain traits to be passed on to the next generation. When the cell is not in the process

Figure 1.10 This drawing shows how DNA is packaged into chromosomes.



of dividing, the chromosomes are not present as visible structures. During this phase the cell's DNA is in the form of chromatin. Chromatin is formed of strands of DNA and proteins called histones. The DNA and histone combination often results in structures called a nucleosome. A nucleosome consists of eight spherical histones with a strand of DNA wrapped around them and secured with a ninth histone. This produces a structure that resembles a string of beads. A chromosome is a highly coiled structure of many nucleosomes.

The nucleus is often located centrally within the cell's cytoplasm, although in some cell types it is pushed to one side or the other. The side position is characteristic of plant cells because these cells often have a large central vacuole. Most eukaryotic cells possess a single nucleus, but some do not have a nucleus at all, and some have multiple nuclei. Without a nucleus, cells cannot reproduce. The loss of reproductive ability is often paired with increased specialization to carry out a certain function. For example, human red blood cells do not have nuclei: they are specialized to transport respiratory gases. Most nuclei also include one or more dark areas called nucleoli (singular nucleolus). Ribosome molecules are manufactured in the nucleolus. The molecules pass through the nuclear envelope before assembling as ribosomes.

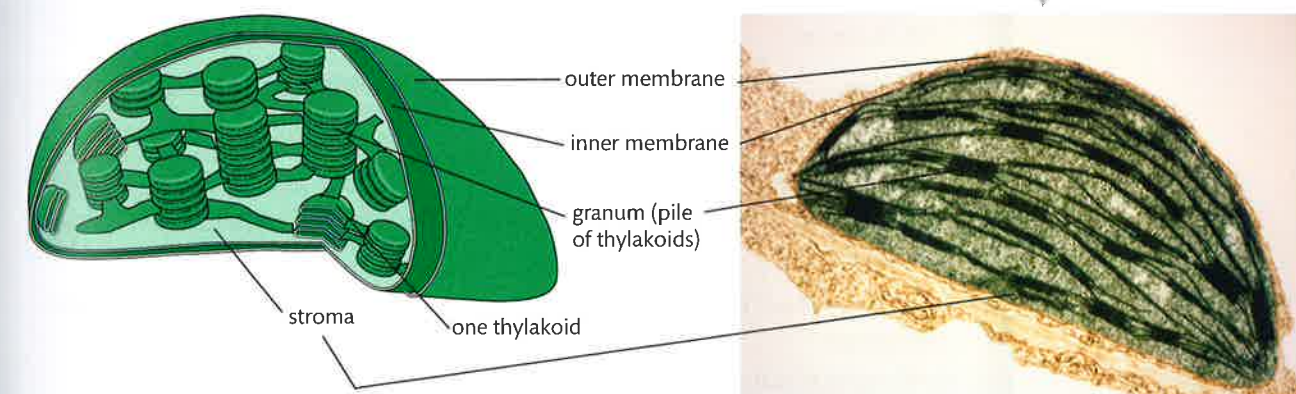
Chloroplasts

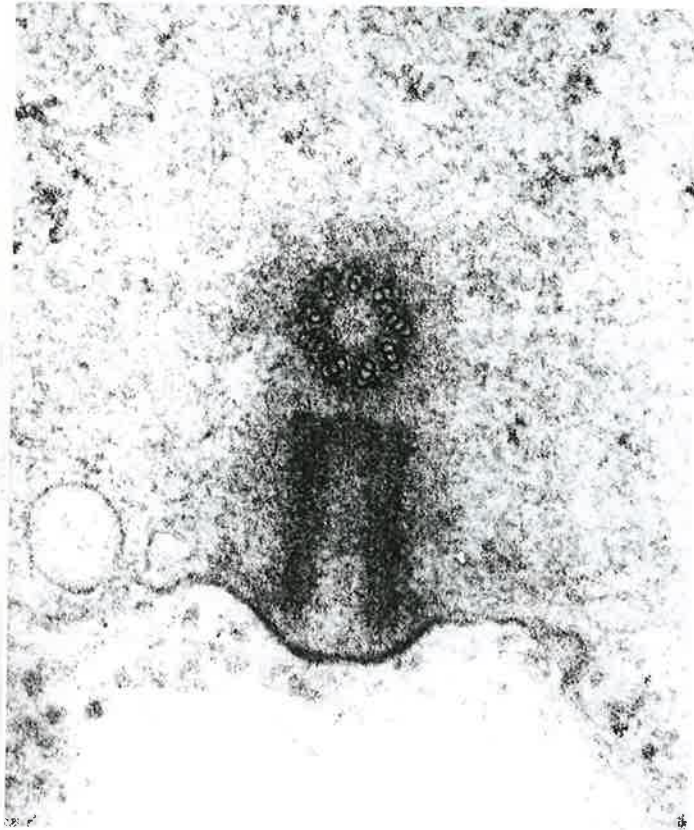
Chloroplasts occur only in algae and plant cells. The chloroplast contains a double membrane and is about the same size as a bacterial cell. Like the mitochondrion, a chloroplast contains its own DNA and 70S ribosomes. The DNA of a chloroplast takes the form of a ring.

You should note all the characteristics that chloroplasts and mitochondria have in common with prokaryotic cells.

As well as DNA and ribosomes, the interior of a chloroplast includes the grana (singular granum), the thylakoids, and the stroma, which are labelled in Figure 1.11. A granum is made up of numerous thylakoids stacked like a pile of coins. The thylakoids are flattened membrane sacs with components necessary for the absorption of light. Absorption of light is the first step in the process of photosynthesis. The fluid stroma is similar to the cytosol of the cell. It occurs outside the grana but within the double membrane. Stroma contains many enzymes and chemicals that are necessary to complete the process of photosynthesis. Like mitochondria, chloroplasts are capable of reproducing independently of a cell.

Figure 1.11 Compare the drawing of a chloroplast with this TEM of a chloroplast.





This TEM shows the two centrioles of a centrosome.

Centrosome

The centrosome occurs in all eukaryotic cells. Generally, it consists of a pair of centrioles at right angles to one another. These centrioles are involved with the assembly of microtubules, which are important to a cell because they provide structure and allow movement. Microtubules are also important for cell division. Cells from higher plants, plants that are thought to have evolved later, produce microtubules even though they do not have centrioles. The centrosome is located at one end of the cell close to the nucleus.

Vacuoles

Vacuoles are storage organelles that are usually formed from the Golgi apparatus. They are membrane-bound and have many possible functions. They occupy a very large space inside the cells of most plants. They may store a number of different substances, including potential food (to provide nutrition), metabolic waste and toxins (to be expelled from the cell), and water. Vacuoles enable cells to have higher surface area to volume ratios even at larger sizes. In plants, they allow the uptake of water, which provides rigidity to the organism.

A comparison of prokaryotic and eukaryotic cells

A table is a good way to summarize the differences between prokaryotic and eukaryotic cells.

Table 1.3 Comparing prokaryotic and eukaryotic cells

Prokaryotic cells	Eukaryotic cells
DNA in a ring form without protein	DNA with proteins as chromosomes/chromatin
DNA free in the cytoplasm (nucleoid region)	DNA enclosed within a nuclear envelope (nucleus)
No mitochondria	Mitochondria present
70S ribosomes	80S ribosomes
No internal compartmentalization to form organelles	Internal compartmentalization present to form many types of organelles
Size less than 10 μm	Size more than 10 μm

If asked to state the similarities between the two types of cells, make sure you include the following:

- both types of cell have some sort of outside boundary that always involves a plasma membrane
- both types of cell carry out all the functions of life
- DNA is present in both cell types.

A comparison of plant and animal cells and their extracellular components

We will now look at how to compare two general types of eukaryotic cell: plant and animal cells. A table like the one below can be used to highlight the differences. However, do not forget to also recognize the similarities between the two cell types.

Table 1.4 Comparing plant and animal cells

Plant cells	Animal cells
The exterior of the cell includes an outer cell wall with a plasma membrane just inside	The exterior of the cell only includes a plasma membrane. There is no cell wall
Chloroplasts are present in the cytoplasm area	There are no chloroplasts
Large centrally located vacuoles are present	Vacuoles are not usually present or are small
Carbohydrates are stored as starch	Carbohydrates are stored as glycogen
Do not contain centrioles within a centrosome area	Contain centrioles within a centrosome area
Because a rigid cell wall is present, this cell type has a fixed, often angular, shape	Without a cell wall, this cell is flexible and more likely to be a rounded shape

Most cell organelles are present in both plant and animal cells. When an organelle is present in both types of cell, it usually has the same structure and function. For example, both cell types contain mitochondria that possess cristae, a matrix, and a double membrane. Also, in both cell types, the mitochondria function in the production of ATP for use by the cell.

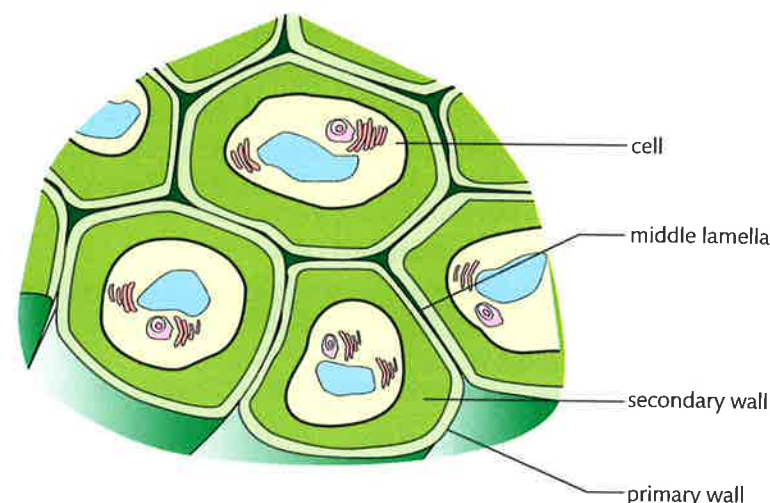
The outermost region of various cell types is often unique to that cell type, as shown by the following table.

Table 1.5 Outermost parts of different cells

Cell	Outermost part
Bacteria	Cell wall of peptidoglycan
Fungi	Cell wall of chitin
Yeasts	Cell wall of glucan and mannan
Algae	Cell wall of cellulose
Plants	Cell wall of cellulose
Animals	No cell wall, instead a plasma membrane that secretes a mixture of sugar and proteins called glycoproteins that forms the extracellular matrix

When comparing items, be certain to state the characteristic of each type of item, as shown in the table for prokaryotic and eukaryotic cells.

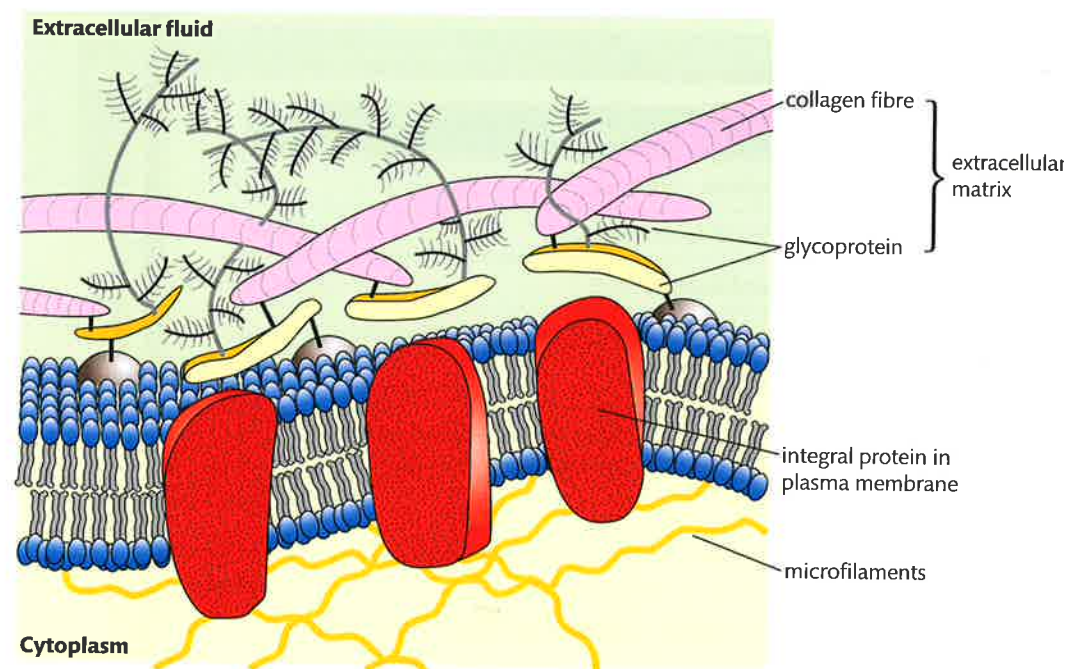
Figure 1.12 This drawing of a section through plant cells shows the primary walls, middle lamella and secondary walls.



Whenever a cell wall is present, it is involved in maintaining cell shape. It also helps regulate water uptake. Because of its rigidity it will only allow a certain amount of water to enter the cell. In plants, when an adequate amount of water is inside the cell, there is pressure against the cell wall. This pressure helps support the plant vertically.

The extracellular matrix (ECM) of many animal cells is composed of collagen fibres plus a combination of sugars and proteins called glycoproteins. These form fibre-like structures that anchor the matrix to the plasma membrane. This strengthens the plasma membrane and allows attachments between adjacent cells. The ECM allows cell-to-cell interactions, possibly altering gene expression and enabling the coordination of cell actions within the tissue. Many researchers think the ECM is involved in directing stem cells to differentiate. Cell migration and movement also appear to be, at least partially, the result of interactions in this area.

Figure 1.13 This is a drawing of the extracellular matrix of an animal cell.



The use of a light microscope to investigate cells and cell structure sizes

***Safety alerts:** Be very cautious with sharp instruments. Wash your hands thoroughly with soap and water before and after handling cell sources. Follow all additional teacher safety directives.*

This practical will develop your skill in using a microscope, allow you to observe some common cells microscopically, and demonstrate ways to calculate the size of cells and cell parts. There are many different types of compound light microscope. Before beginning this practical, it is essential you understand how to use your school's microscopes properly. As well as a microscope, other materials necessary for this practical include microscope slides, cover glasses, methylene blue in a dropper bottle, water in a dropper bottle, a plastic ruler, toothpicks, and several sources of cells.

1 Determine the total magnification of each objective lens

Because you are using a compound microscope, there are two types of lens present. One is the ocular lens and the other is the objective lens. Each of these lenses has a number on it followed by an \times . These numbers represent the magnification of that particular lens. To determine the total magnification of an object being examined with the microscope, multiply the power of the ocular lens by the power of the objective lens. Carry out this procedure for each of the microscope objective lenses you use and record the information required in the following table.

Table 1.6 Microscope total magnification and diameter of field of view

Power of ocular lens	Power of objective lens	Total magnification	Diameter of field of view (mm)	Diameter of field of view (μm)
Low				
Medium				
High				

2 Determine the diameter of the field of view

The field of view (field of vision) is the circular area you can see when you look through the ocular lens of a microscope. It is important to know its diameter. One way to determine this is to place a plastic ruler under the low-power objective lens so that it crosses the diameter of the field of view. Observe and record the diameter in millimetres in the above table. Repeat the same procedure for the next two objectives to determine the diameter of their field of view. Instead of using a ruler for the two higher power objectives, you can use proportions to determine the field of view by comparing their diameters with the diameter determined for the lowest power. Convert millimetre (mm) measurements to microns (micrometres; μm):

$$1 \text{ mm} = 1000 \mu\text{m}$$

3 Observing and determining the sizes of cells

- You will now look at several types of cells. Prepared slides may be used or you can make your own wet-mount slides. Your teacher will provide the information you need to produce a wet mount.
- Some ideas for producing your own wet-mount slides include: the inside epidermal layer from the bulb of an onion; *Elodea* leaf cells; *Anabaena* (an aquatic cyanobacterium); cheek cells from inside your mouth; scraped soft banana tissue.
- Whatever cells are used, study them carefully, noting any internal structures, and their size in relation to the rest of the cell and its visible parts. Using a stain such as methylene blue or iodine often means you can see the parts of a cell more clearly. Use any resources available, including texts and the internet, to identify any structures you can see.
- For each cell type you observe, complete the following steps.
 - Using a pencil, draw several typical cells seen in the field of view. Label any visible cell structures.

(ii) Carefully and accurately make a scale drawing of these cells and any visible internal parts.

(iii) Beside each drawing include the:

- total magnification
- diameter of the field of view
- estimated length of an individual cell.

To figure out the length of one cell, divide the diameter of the field of view by the number of cells that cross the diameter of the field of view. This value should be recorded in microns (μm).

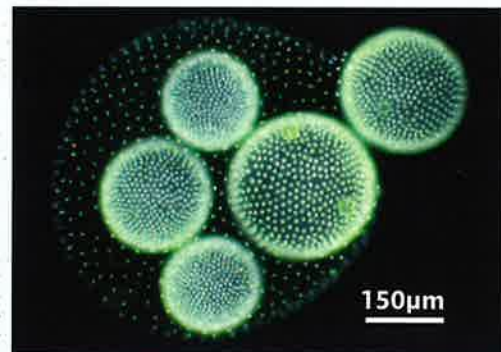
Another way to determine the size of objects in the field of view of a microscope is to use an eyepiece graticule. Graticules must be calibrated. To calibrate a graticule, a plastic millimetre ruler or a graduated slide can be used. While using the lowest power objective lens, move the graduated slide until the graticule scale and the graduated slide scale align. The size of the graticule units can now be determined. You can follow the same procedure to calibrate the other two objectives, or you can calculate the other calibrations. Once you have calibrated the graticule, it can be used to take accurate measurements of the object being viewed.

4 Microscope magnification and cell size

We will complete this activity with some problems involving cell size and magnification. Use this general formula for calculating magnification:

$$\text{magnification} = \text{drawing size} / \text{actual size}$$

- (a) An organism has an actual length of 0.01 mm. If you draw a diagram that is 50 mm, what is the magnification of your drawing?
- (b) Scale bars are lines added to a micrograph (the photograph of an image under a microscope) or a drawing to represent the actual size of the structures. For example, a 25- μm bar would represent the size of a 25- μm image. The picture below shows an image of several *Volvox* seen in a microscope field of view. Use the scale bar to determine the approximate size of the three central, fully shown *Volvox*.



- (c) An organism has an actual length of 0.05 mm. If you use a scale of 1:200, what will the size of your drawing of the organism be?
- (d) You should look at more images of micrographs on the internet to develop your skills in determining the sizes of cells and cell structures. Be certain to include electron micrographs in your practice.

Exercises

- What is a disadvantage to prokaryotic cells of having their DNA free in the cytoplasm without a nuclear membrane?
- What structures are involved in sexual reproduction in prokaryotic cells?
- Dental plaque involves the presence of bacteria. Explain how the bacteria are able to attach firmly to teeth such that the bacteria can only be removed with scraping.
- Why do muscle cells have a large number of mitochondria?
- Name two organelles that are similar to prokaryotic cells.
- If plant cells have chloroplasts for photosynthesis, why do they also need mitochondria?
- What is the importance of scale bars on micrographs?

To learn more about prokaryotic and eukaryotic cells, and the features of bacterial cells, go to the hotlinks site, search for the title or ISBN, and click on Chapter 1: Section 1.2.

1.3 Membrane structure

Understandings:

- Phospholipids form bilayers in water due to the amphipathic properties of phospholipid molecules.
- Membrane proteins are diverse in terms of structure, position in the membrane, and function.
- Cholesterol is a component of animal cell membranes.

Applications and skills:

- Application: Cholesterol in mammalian membranes reduces membrane fluidity and permeability to some solutes.
- Skill: Drawing of the fluid mosaic model.
- Skill: Analysis of evidence from electron microscopy that led to the proposal of the Davson–Danielli model.
- Skill: Analysis of the falsification of the Davson–Danielli model that led to the Singer–Nicolson model.

Guidance

- Amphipathic phospholipids have hydrophilic and hydrophobic properties.
- Drawings of the fluid mosaic model of membrane structure can be two-dimensional rather than three-dimensional. Individual phospholipid molecules should be shown using the symbol of a circle with two parallel lines attached. A range of membrane proteins should be shown including glycoproteins.

Membrane structure

As early as 1915 scientists were aware that the structure of membranes isolated from cells included proteins and lipids. Further research established that the lipids were phospholipids. Early theories were mostly concerned with phospholipids forming a bilayer with proteins, forming thin layers on the exterior and interior of the bilayer. The Davson–Danielli model, proposed by Hugh Davson and James Danielli in 1935, used this lipid bilayer model, suggesting it was covered on both sides by a thin layer of globular protein.

In 1972, Seymour J. Singer and Garth L. Nicolson proposed that proteins are inserted into the phospholipid layer and do not form a layer on the phospholipid bilayer surfaces. They believed that the proteins formed a mosaic floating in a fluid layer of phospholipids. There were several reasons why Singer and Nicolson proposed a model that was different from the Davson–Danielli model. These reasons included the following.

- Not all membranes are identical or symmetrical, as the first model implied.
- Membranes with different functions also have a different composition and different structure, as can be seen with an electron microscope.
- A protein layer is not likely because it is largely non-polar and would not interface with water, as shown by cell studies.

Much of the evidence used to change the Davson–Danielli model was gathered with the use of the electron microscope. Another source of evidence was the study of cells and their actions in various environments and solutions. The ability to culture cells in the laboratory allowed many of these studies. Since 1972 further evidence has been gathered about membranes, and slight changes to the Singer–Nicolson model have been made.



NATURE OF SCIENCE

Using models as representations of the real world: there are alternative models of membrane structure.

Falsification of theories, with one theory being superseded by another: evidence falsified the Davson–Danielli model.

TOK

Using models is a way in which scientists explain complex structures such as cellular membranes. Models are based on the knowledge available at the time a theory is suggested. Even though the early models of cell membranes were later proved wrong (because of new data), they helped in the development of the presently accepted model of cell membranes. Discuss why it is important to learn about theories that are later discredited.

The current agreed model for the cellular membrane is the fluid mosaic model. It is shown in the following diagram. All cellular membranes, whether plasma membranes or organelle membranes, have the same general structure.

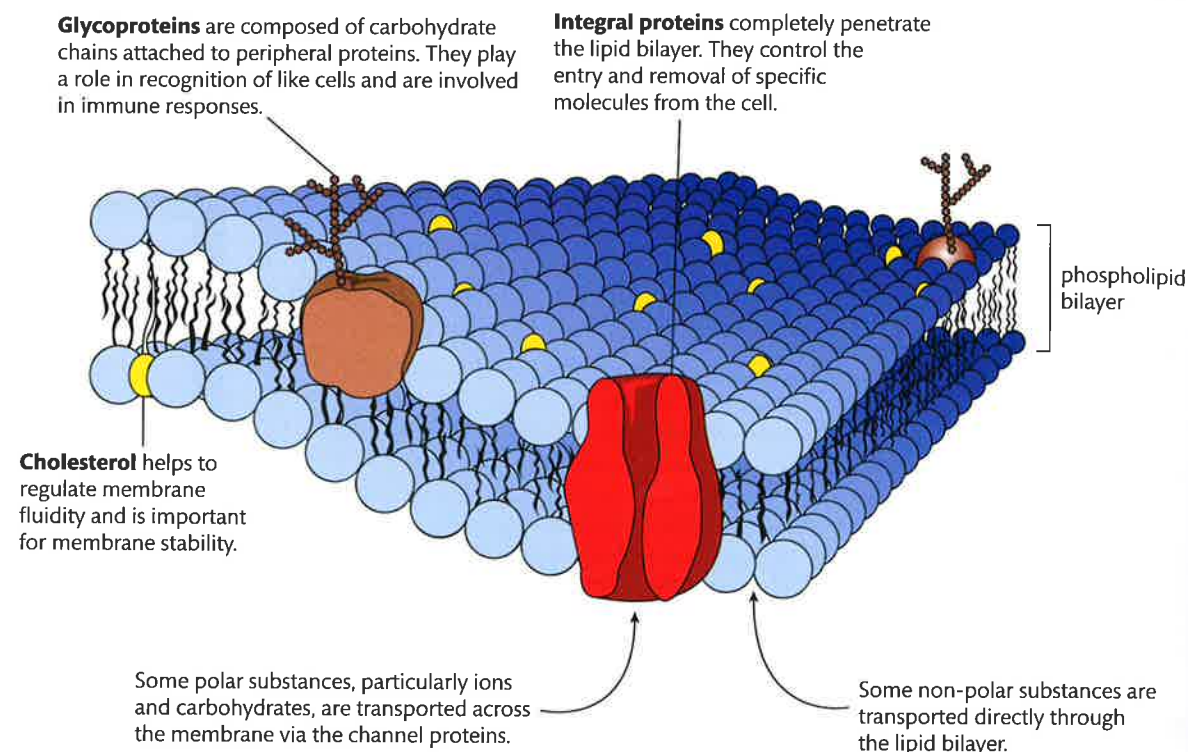
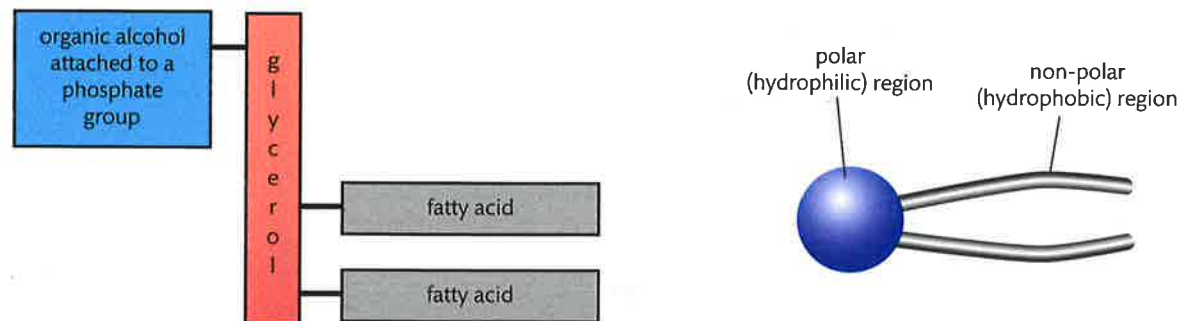


Figure 1.14 In the fluid mosaic model of the cell membrane there is a double layer of lipids (fats) arranged with their tails facing inwards. Proteins are thought to 'float' in the lipid bilayer.

Phospholipids

In Figure 1.14 note that the 'backbone' of the membrane is a bilayer produced from huge numbers of molecules called phospholipids. Each phospholipid is composed of a three-carbon compound called glycerol. Two of the glycerol carbons have fatty acids. The third carbon is attached to a highly polar organic alcohol that includes a bond to a phosphate group. Fatty acids are not water soluble because they are non-polar. In contrast, because the organic alcohol with phosphate is highly polar, it is water soluble. This structure means that membranes have two distinct areas when it comes to polarity and water solubility. One area is water soluble and polar, and is referred to as hydrophilic (water-loving). This is the phosphorylated alcohol side. The other area is not water soluble and is non-polar. It is referred to as hydrophobic (water-fearing).

Figure 1.15 This is a model of a phospholipid.



The hydrophobic and hydrophilic regions cause phospholipids to align as a bilayer if there is water present and there is a large number of phospholipid molecules. Because the fatty acid 'tails' do not attract each other strongly, the membrane tends to be fluid or flexible. This allows animal cells to have a variable shape and also allows the process of endocytosis (which is discussed below) to take place. What maintains the overall structure of the membrane is the tendency water has to form hydrogen bonds.

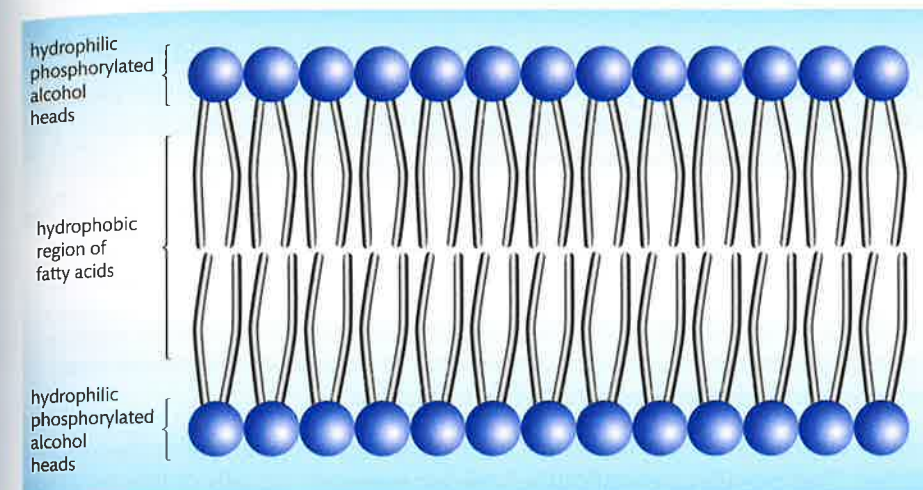


Figure 1.16 This model of a phospholipid bilayer shows how phospholipid molecules behave in two layers. Both layers have the phosphorylated alcohol end of the molecules towards the outside and the fatty acid tails oriented towards each other in the middle.

Cholesterol

Membranes must be fluid to function properly. They are a bit like olive oil in their consistency. At various locations in the hydrophobic region (fatty acid tails) in animal cells are cholesterol molecules. These molecules have a role in determining membrane fluidity, which changes with temperature. The cholesterol molecules allow membranes to function effectively at a wider range of temperatures than if they were not present. Plant cells do not have cholesterol molecules; they depend on saturated or unsaturated fatty acids to maintain proper membrane fluidity.

Proteins

The last major component of cellular membranes comprises the proteins. It is these proteins that create the extreme diversity in membrane function. Proteins of various types are embedded in the fluid matrix of the phospholipid bilayer. This creates the mosaic effect referred to in the fluid mosaic model. There are usually two major types of proteins. One type is referred to as integral proteins and the other type is referred to as peripheral proteins. Integral proteins show an amphipathic character, with both hydrophobic and hydrophilic regions within the same protein. These proteins will have the hydrophobic region in the mid-section of the phospholipid backbone. Their hydrophilic region will be exposed to the water solutions on either side of the membrane. Peripheral proteins, on the other hand, do not protrude into the middle hydrophobic region, but remain bound to the surface of the membrane. Often these peripheral proteins are anchored to an integral protein. Look at the drawing of the fluid mosaic model (Figure 1.14) to see the location of these proteins.

Make sure you can draw and label all the parts of a membrane as described in this section for the fluid mosaic model. Follow the directions given earlier for making a good drawing. In the drawing, the phospholipids should be shown using the symbol of a circle with two parallel lines attached. It is also important to show a wide range of proteins with various functions and locations.

Membrane protein functions

As you will recall, it is the membrane proteins that impart different functions to the different membranes. There are many different proteins, which have six general functions:

- sites for hormone-binding
- enzymatic action
- cell adhesion
- cell-to-cell communication
- channels for passive transport
- pumps for active transport.

Proteins that serve as hormone-binding sites have specific shapes exposed to the exterior that fit the shape of specific hormones. The attachment between the protein and the hormone causes a change in the shape of the protein, which results in a message being relayed to the interior of the cell.

Cells have enzymes attached to membranes that catalyse many chemical reactions. The enzymes may be on the interior or the exterior of the cell. Often they are grouped so that a sequence of metabolic reactions, called a metabolic pathway, can occur.

Cell adhesion is provided by proteins that can they hook together in various ways to provide permanent or temporary connections. These connections, referred to as junctions, can include gap junctions and tight junctions.

Many of the cell-to-cell communication proteins have carbohydrate molecules attached. They provide an identification label that represents the cells of different types of species.

Some proteins contain channels that span the membrane, providing passageways for substances to be transported through. When this transport is passive, material moves through the channel from an area of high concentration to an area of lower concentration.

In active transport, proteins shuttle a substance from one side of the membrane to another by changing shape. This process requires the expenditure of energy in the form of ATP. It does not require a difference in concentration to occur.

Exercises

- 12 Explain the orientation of the bilayer of phospholipid molecules in the plasma membrane using the terms hydrophobic and hydrophilic.
- 13 Why does a diet high in plants and plant products have relatively low cholesterol levels compared with a diet involving high amounts of animal products?
- 14 What type of properties do amphipathic phospholipids possess?
- 15 What do many of the proteins of the plasma membrane involved with cell-to-cell communication have attached to them?

A passive process does not need the cell to provide any energy for it to occur. If energy is needed for a process to occur, that process is called active and the form of energy most often used is a type of nucleic acid called adenosine triphosphate or ATP.

1.4 Membrane transport

Understandings:

- Particles move across membranes by simple diffusion, facilitated diffusion, osmosis, and active transport.
- The fluidity of membranes allows materials to be taken into cells by endocytosis or released by exocytosis. Vesicles move materials within cells.

Applications and skills:

- Application: Structure and function of sodium-potassium pumps for active transport and potassium channels for facilitated diffusion in axons.
- Application: Tissues or organs to be used in medical procedures must be bathed in a solution with the same osmolarity as the cytoplasm to prevent osmosis.
- Skill: Estimation of osmolarity in tissues by bathing samples in hypotonic and hypertonic solutions.

Guidance

- Osmosis experiments are a useful opportunity to stress the need for accurate mass and volume measurements in scientific experiments.

Passive and active transport

There are two general types of cellular transport:

- passive transport
- active transport.

As mentioned previously, passive transport does not require energy (in the form of ATP), but active transport does. Passive transport occurs in situations where there are areas of different concentrations of a particular substance. Movement of the substance occurs from an area of higher concentration to an area of lower concentration. Movement is said to occur along a concentration gradient.

When active transport occurs, the substance is moved against a concentration gradient, so energy expenditure must occur.

Passive transport: diffusion and osmosis

Examine Figure 1.17. It shows chemical diffusion.

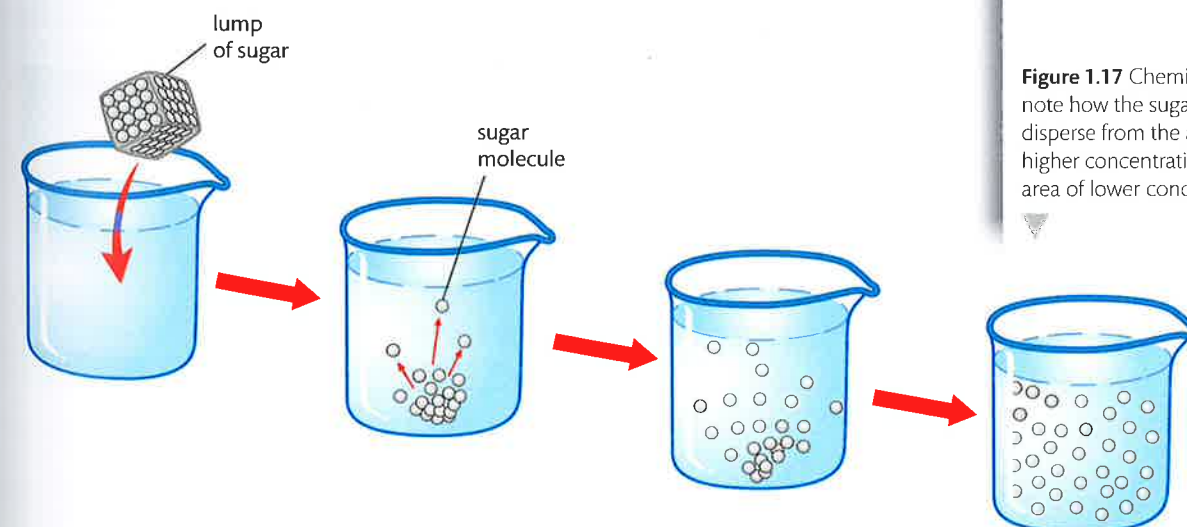


Figure 1.17 Chemical diffusion: note how the sugar molecules disperse from the area of higher concentration to the area of lower concentration.

NATURE OF SCIENCE

Experimental design: accurate quantitative measurements in osmosis experiments are essential.

Diffusion

Diffusion is one type of passive transport. Particles of a certain type move from a region of higher concentration to a region of lower concentration. However, in a living system, diffusion often involves a membrane. For example, oxygen gas moves from outside a cell to inside that cell. Oxygen is used by the cell when its mitochondria carry out respiration, thus creating a relatively lower oxygen concentration inside the cell compared with outside the cell. Oxygen diffuses into the cell as a result. Carbon dioxide diffuses in the opposite direction to the oxygen because carbon dioxide is produced as a result of mitochondrial respiration.

Facilitated diffusion

Facilitated diffusion is a particular type of diffusion involving a membrane with specific carrier proteins that are capable of combining with the substance to aid its movement. The carrier protein changes shape to accomplish this task but does not require energy.

It should be evident from this explanation that facilitated diffusion is very specific depending on the carrier protein. The rate of facilitated diffusion will level off when total saturation of the available carriers occurs.

Osmosis

Osmosis is another type of passive transport: movement occurs along a concentration gradient. However, osmosis involves only the passive movement of water across a partially permeable membrane. A partially permeable membrane is one that only allows certain substances to pass through (a permeable membrane would allow everything through). A concentration gradient of water that allows the movement to occur is the result of a difference between solute concentrations on either side of a partially permeable membrane. A hypertonic (hyperosmotic) solution has a higher concentration of total solutes than a hypotonic (hypo-osmotic) solution. Water therefore moves from a hypotonic solution to a hypertonic solution across a partially permeable membrane (study Figure 1.18). If isotonic solutions occur on either side of a partially permeable membrane, no net movement of water is evident.

Table 1.7 summarizes diffusion and osmosis (passive transport) across cellular membranes.

Table 1.7 Diffusion and osmosis

Type of passive transport	Description of membrane
Simple diffusion	Substances other than water move between phospholipid molecules or through proteins that possess channels
Facilitated diffusion	Non-channel protein carriers change shape to allow movement of substances other than water
Osmosis	Only water moves through the membrane using aquaporins, which are proteins with specialized channels for water movement

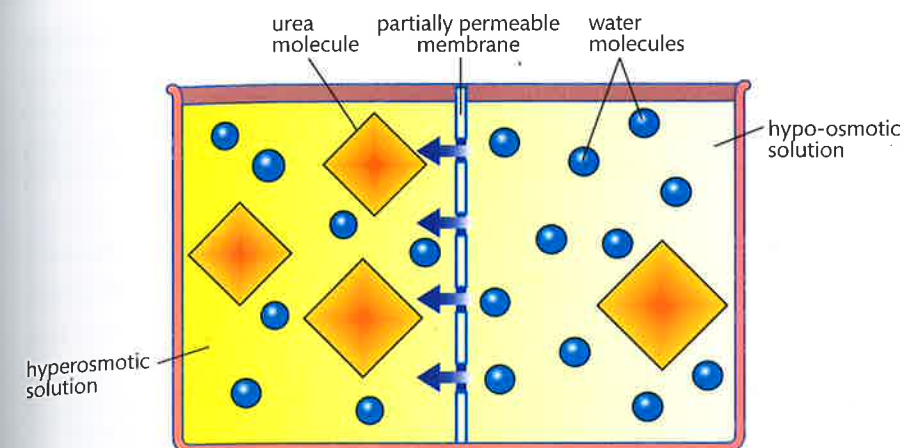


Figure 1.18 The partially permeable membrane between two solutions of different osmotic concentrations allows water molecules to pass from the hypo-osmotic solution to the hyperosmotic solution.

Size and charge

The size and polarity of molecules determine the ease with which various substances can cross membranes. These characteristics and the ability of molecules to cross membranes are arranged along a continuum like this:

small and non-polar molecules cross membranes easily \longleftrightarrow large and polar molecules cross membranes with difficulty

How easily a substance can move across a membrane passively depends on two major factors: size and charge. Substances that are small in size and non-polar will move across a membrane with ease. Substances that are polar, large in size, or both, do not cross membranes easily. Examples of small, non-polar substances are gases such as oxygen, carbon dioxide, and nitrogen. Ions such as chloride ions, potassium ions, and sodium ions have a great deal of difficulty crossing membranes passively, as do large molecules such as glucose and sucrose. Molecules such as water and glycerol are small, uncharged polar molecules that can cross membranes fairly easily.

A practical example of diffusion and osmosis is kidney dialysis. Many people have problems regulating blood solutes (solutes are substances that are dissolved in a solvent, in this case blood, to form a solution).

Solutions occur throughout the body in various types of spaces: intracellular spaces occur inside cells; extracellular spaces occur outside cells; interstitial spaces occur between cells; intravascular spaces occur within blood vessels.

Problems in regulating the solutes in the many body spaces can arise as the result of some sort of irregularity in the function of the kidneys. This can ultimately threaten a person's life because of the lack of homeostatic levels of solutes. To re-establish homeostasis, a process called haemodialysis may be carried out.

In this process, blood is passed through a system of tubes composed of selectively permeable membranes. These tubes are surrounded with a solution that is referred to as the dialysate. The dialysate contains key solutes at levels close to the patient's normal blood levels. Wastes are kept at a low level in the dialysate. As blood moves through the tubes, the dialysate is constantly replaced to maintain ideal levels.

An example of a disease involving facilitated diffusion is cystinuria. This occurs when the protein that carries the amino acid cysteine is absent from kidney cells. The result is a build-up of amino acids in the kidney, resulting in very painful kidney stones.

Partially permeable membranes are also called selectively permeable membranes. Passive transport will occur until there is an equal concentration of the substance in both areas involved. This is called equilibrium.

An aid to remembering the difference between diffusion and osmosis is 'H₂Osmosis', linking the solvent water to osmosis.

CHALLENGE YOURSELF

Use your knowledge of osmosis, diffusion, membrane transport, and kidney dialysis to answer the following questions.

- When solutes move from the blood through the selectively permeable membrane into the dialysate, what process is occurring?
- Why is the process that allows wastes to move from the blood to the dialysate referred to as passive?
- What is the importance of constantly changing the dialysate?
- Name some characteristics of solutes in blood that would affect their rate of movement through the selectively permeable membrane.
- Haemodialysis also allows regulation of water concentrations within the blood. What process is occurring when water moves through the tube membranes into the dialysate?
- What factors might affect the time necessary for dialysis to bring about homeostatic blood levels of solutes and wastes?

Dialysis is also an example of how cell or tissue osmolarity (the concentration of osmotically active particles) can be estimated. If cells are placed in a solution of known osmolarity, there are three possibilities: the cells may gain mass, the cells may lose mass, or the cells may remain at the same mass. Answer the following questions.

- If a group of cells are placed in a hypotonic solution, what will happen to their mass? Explain your answer.
- One way to stop undesirable plants growing at a specific location is to apply a solution of water with a high concentration of sodium chloride (table salt). Why does this kill the plants and prevent their return for a period of time?



Determining the osmolarity of tissues

Safety alerts. Use safety goggles and lab aprons. Be cautious of cork borers and any other sharp instruments used. Wash your hands thoroughly with soap and water after each day's procedures.

Follow these instructions to determine the osmolarity of tissues by bathing samples in hypotonic, isotonic, and hypertonic solutions. The instructions use potatoes as a source of tissue, but other tissues could be used.

- With a cork borer, cut six cores from a potato. The cores should all be as close to the same length as possible: 30–50-mm cores are recommended. Each core should be kept separate and identified as core A, core B, core C, core D, core E, and core F.
- Before continuing, produce a table that will show the volume and mass of the potato cores before and after being placed in solutions of six different sucrose molarities. The molarities to be used are 0.0 M, 0.2 M, 0.4 M, 0.6 M, 0.8 M, and 1.0 M.
- Using an appropriately sized graduated cylinder approximately one-half filled with water, determine the volume of each core using fluid displacement. **Record** this information.
- Once each core is removed from the graduated cylinder, blot it dry with a paper towel and determine its mass using a laboratory balance. Record your results in the table.
- Place each core in a different test tube labelled with the core's identification letter and the molarity of the sucrose solution to be placed in the tube.
- Add a labelled molar solution to each test tube until the core is covered. Place foil or plastic wrap over each tube and store for 24 hours.
- On the next day, repeat steps 3 and 4. Record your 24-hour results in the table.
- Data processing
 - Produce a table to record the processed data involving the percentage change in mass and core volume.
 - Calculate the percentage change in mass, and the percentage change in volume, at the end of 24 hours, for each core. Record your results in the processed data table.
 - Construct an appropriate graph, with the independent variable of sucrose molarity on the x-axis and the dependent variable of mass percentage change on the y-axis.
 - Construct a similar graph showing volume percentage change.
- Analysis
 - What is the osmolarity of the potato tissue? Explain how you determined this.
 - Explain the importance of accurate mass and volume measurements in this procedure, and in all scientific experiments.
 - Suggest some ways in which this procedure could be altered so that more reliable data could be attained.

Active transport and the cell

As you will remember, active transport requires work to be performed. This means energy must be used, so ATP is required. Active transport involves the movement of substances against a concentration gradient. This process allows a cell to maintain interior concentrations of molecules that are different from exterior concentrations.

Animal cells have a much higher concentration of potassium ions than their exterior environment, whereas sodium ions are more concentrated in the extracellular environment than in the cells. The cell maintains these conditions by pumping potassium ions into the cell and pumping sodium ions out of it. Along with energy, a membrane protein must be involved for this process to occur.

The sodium–potassium pump

The mechanism for actively moving sodium and potassium ions, the sodium–potassium pump, has five stages.

- A specific protein binds to three intracellular sodium ions.

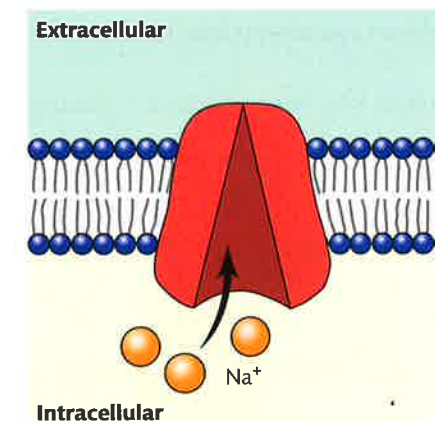


Figure 1.19 Stage 1: A protein in a phospholipid bilayer opens to the intracellular side and attaches three sodium ions.

- The binding of sodium ions causes phosphorylation by ATP. ATP has three attached phosphates. When it carries out phosphorylation, one phosphate is lost resulting in a two-phosphate compound called ADP. ATP and ADP are discussed in more detail in Chapter 2.

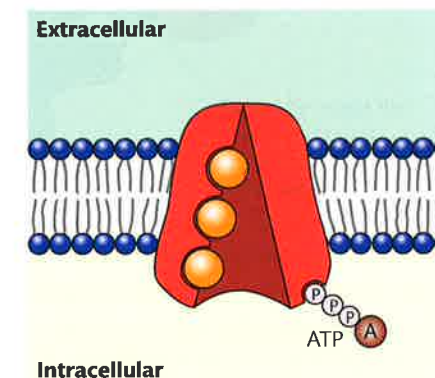


Figure 1.20 Stage 2: ATP attaches to the protein.

- The phosphorylation causes the protein to change its shape, thus expelling sodium ions to the exterior.

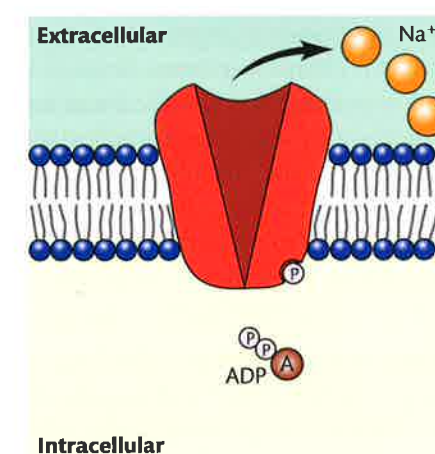


Figure 1.21 Stage 3: The carrier opens to the exterior of the cell and the sodium ions are released. ADP is released, leaving a phosphate group attached to the protein.

- 4 Two extracellular potassium ions bind to different regions of the protein, and this causes the release of the phosphate group.

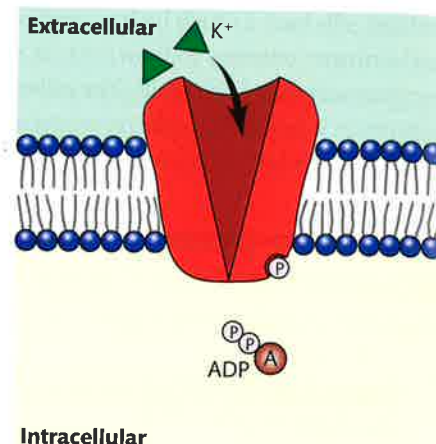


Figure 1.22 Stage 4: Extracellular potassium ions attach to the protein.

- 5 The loss of the phosphate group restores the protein's original shape, thus causing the release of the potassium ions into the intracellular space.

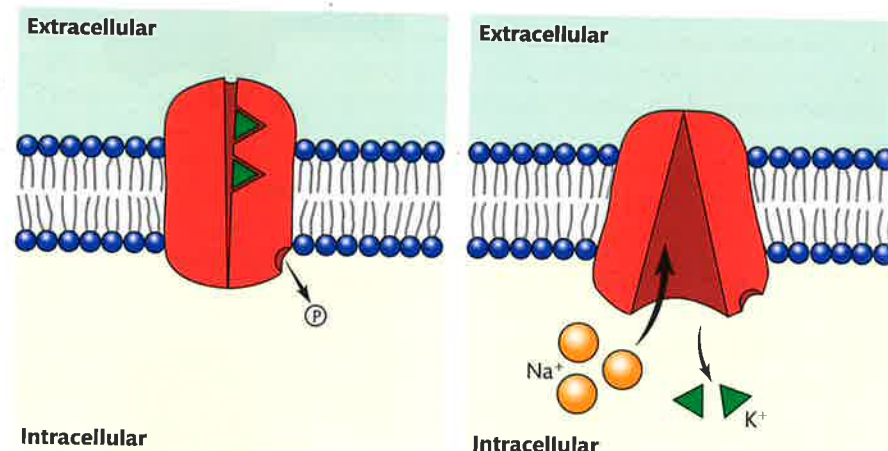


Figure 1.23 Stage 5: The protein opens towards the cell interior again and releases the potassium ions into the interior.

There are many other examples of active transport in cells besides the sodium-potassium pump. Liver cells use active transport to accumulate glucose molecules from blood plasma even though the liver has a higher glucose concentration.

Cystic fibrosis is a human genetic disease in which the membrane protein that transports chloride ions is missing. This causes high concentrations of water inside the cells that line the lungs, and abnormally thickened mucus production. It is a very serious condition.

The sodium-potassium pump shows how important and active specific proteins are in the active transport of particular substances. It is also clear how ATP plays a crucial role in active transport.

Endocytosis and exocytosis

Endocytosis and exocytosis are processes that allow larger molecules to move across the plasma membrane. Endocytosis allows macromolecules to enter the cell, while exocytosis allows molecules to leave. Both processes depend on the fluidity of the plasma membrane. It is important to recall why the cell membranes are fluid in consistency: the phospholipid molecules are not closely packed together, largely because of the rather 'loose' connections between the fatty acid tails. It is also important to remember why the membrane is quite stable: the hydrophilic and hydrophobic properties of the different regions of the phospholipid molecules cause them to form a stable bilayer in an aqueous environment.

Endocytosis occurs when a portion of the plasma membrane is pinched off to enclose macromolecules or particulates. This pinching off involves a change in the shape of the membrane. The result is the formation of a vesicle that then enters the cytoplasm of the cell. The ends of the membrane reattach because of the hydrophobic and

hydrophilic properties of the phospholipids and the presence of water. This could not occur if the plasma membrane did not have a fluid nature.

Exocytosis is essentially the reverse of endocytosis, so the fluidity of the plasma membrane and the hydrophobic and hydrophilic properties of its molecules are just as important as in endocytosis. One example of cell exocytosis involves proteins produced in the cytoplasm of a cell. Protein exocytosis usually begins in the ribosomes of rough ER and progresses through a series of four steps, outlined below, until the substance produced is secreted to the environment outside the cell.

- 1 Protein produced by the ribosomes of the rough ER enters the lumen, inner space, of the ER.
- 2 Protein exits the ER and enters the *cis* side or face of the Golgi apparatus; a vesicle is involved.
- 3 As the protein moves through the Golgi apparatus, it is modified and exits on the *trans* face inside a vesicle.
- 4 The vesicle with the modified protein inside moves to and fuses with the plasma membrane; this results in the secretion of the contents from the cell.

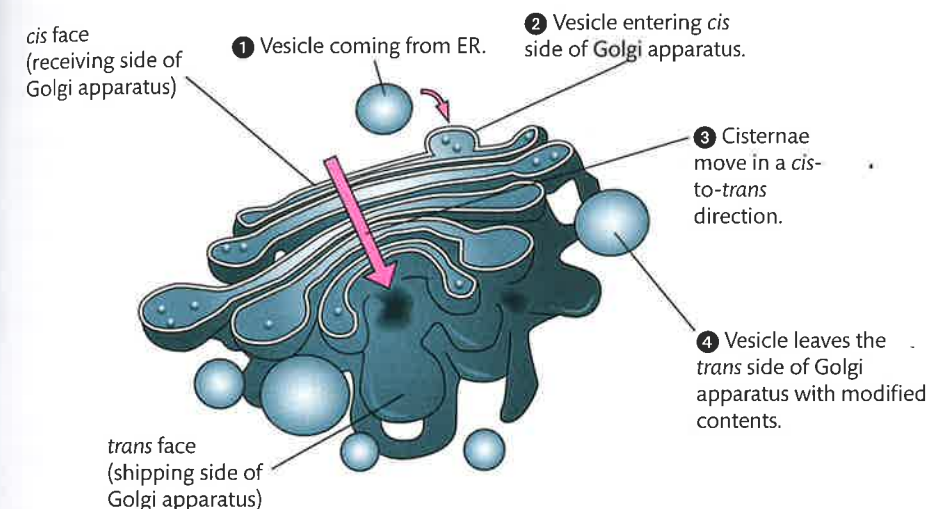


Figure 1.24 How the Golgi apparatus functions.

Examples of exocytosis occur when:

- pancreas cells produce insulin and secrete it into the bloodstream (to help regulate blood glucose levels)
- neurotransmitters are released at synapses in the nervous system.

The fluidity of the plasma membrane is essential to allow fusion and subsequent secretion of the vesicle contents. At this point the vesicle membrane is actually a part of the plasma membrane.

Exercises

- 16 Why is the term equilibrium used with passive but not active transport?
- 17 What type of amino acids will be present where integral proteins attach to cell membranes?
- 18 Why are exocytosis and endocytosis known as examples of active transport?

NATURE OF SCIENCE

Testing the general principles that underlie the natural world: the principle that cells only come from pre-existing cells needs to be verified.



1.5 The origin of cells

Understandings:

- Cells can only be formed by division of pre-existing cells.
- The first cells must have arisen from non-living material.
- The origin of eukaryotic cells can be explained by the endosymbiotic theory.

Applications and skills:

- Application: Evidence from Pasteur's experiments that spontaneous generation of cells and organisms does not now occur on Earth.

Guidance

- Evidence for the endosymbiotic theory is expected. The origin of eukaryote cilia and flagella does not need to be included.
- Students should be aware that the 64 codons in the genetic code have the same meanings in nearly all organisms, but that there are some minor variations that are likely to have accrued since the common origin of life on Earth.

Cell theory

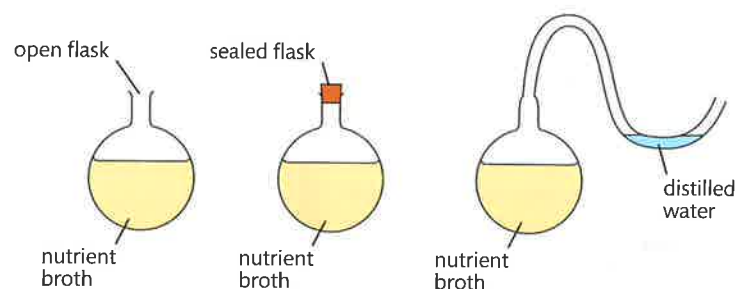
The cell theory was discussed in Section 1.1. We mentioned that the current theory has three main parts:

- 1 all organisms are composed of one or more cells
- 2 cells are the smallest units of life
- 3 all cells come from other pre-existing cells.

We also mentioned that there are some problems with and exceptions to the current cell theory. These exceptions will now be discussed. Scientists use the term theory to represent a well-substantiated explanation of a natural phenomenon that incorporates tested hypotheses and laws. Because of this, a theory is an extremely valuable endpoint of science that represents understandings that have developed from extensive observation, experimentation, and logical inferences. Cell theory is a prime example of this. It has been modified during the years since it was first proposed in the 1800s. It will continue to be modified as cellular research progresses in the future.

One obvious missing component of cell theory is how the first cell arose. There is no evidence that new cells arise from non-living material today. However, the first cells must have been formed in this way. As already mentioned, in the 19th century the famous French scientist Louis Pasteur showed that bacteria could not spontaneously appear in sterile broth. Here is an overview of his experiment.

Figure 1.25 Pasteur's broth experiment.



- 1 He boiled a nutrient broth.
- 2 The now sterile nutrient broth was then placed in three flasks, as shown to the left. Incubation over a period of time was then allowed.
- 3 A sample of each flask was then transferred to a plate containing solid medium and incubated.

The only flask sample that showed the presence of bacteria was the opened one. The other two did not show any bacterial growth. This indicated to Pasteur that the concept of spontaneous generation was wrong.

The Italian scientist Francesco Redi also questioned the concept of spontaneous generation, nearly 200 years before Pasteur, and conducted an experiment using raw meat in jars. Many other experiments have been done since the work of these two science pioneers, casting further doubt on the idea of spontaneous generation.

Moving on to the exceptions to the current cell theory, these include:

- the multinucleated cells of striated muscle cells, fungal hyphae, and several types of giant algae
- very large cells with continuous cytoplasm that are not compartmentalized into separate smaller cells
- viruses
- the problem of explaining the 'first' cells without spontaneous generation.

These examples represent exceptions to the 'normal' cells that we see in most of the organisms on Earth today. Continued research is needed to see how these exceptions 'fit' in with the current cell theory.

A common origin for all cells on Earth requires an explanation of how a cell could progress from a simple, non-compartmentalized prokaryote to a complex, highly compartmentalized eukaryote. This is currently explained by the endosymbiotic theory. This theory was presented by Lynn Margulis in 1981. Key points of the theory include:

- about 2 billion years ago a bacterial cell took up residence inside a eukaryotic cell
- the eukaryotic cell acted as a 'predator', bringing the bacterial cell inside
- the eukaryotic cell and the bacterial cell formed a symbiotic relationship, in which both organisms lived in contact with one another
- the bacterial cell then went through a series of changes to ultimately become a mitochondrion.

In this process, the eukaryote helped the bacteria by providing protection and carbon compounds. The bacteria, after a series of changes, became specialized in providing the eukaryote with ATP. There is a lot of evidence to support this theory. Mitochondria:

- are about the size of most bacterial cells
- divide by fission, as do most bacterial cells
- divide independently of the host cell
- have their own ribosomes, which allows them to produce their own proteins
- have their own DNA, which more closely resembles the DNA of prokaryotic cells than of eukaryotic cells
- have two membranes on their exterior, which is consistent with an engulfing process.

In addition to the mitochondria, chloroplasts in plant cells also provide evidence for the theory of endosymbiosis. A modern-day protist called *Hatena* normally fulfils its nutritional needs by ingesting organic matter. However, when it behaves as a predator and ingests a green alga, it switches its method of fulfilling its nutritional needs to one that uses sunlight to convert organic molecules, a process known as photosynthesis. The two organisms, the *Hatena* and the green alga, continue to thrive in a symbiotic relationship.



Plasmodial slime moulds, of the phylum Myxomycota, are composed of eukaryotic cells. They are found in forests as a single large cell formed when many individual motile cells fuse. These cells have many nuclei and may increase in size to several centimetres. They are even capable of slow but coordinated movement. These organisms certainly present a different image of a cell than usually thought of when discussing the cell theory.



NATURE OF SCIENCE

Now is an ideal time to have a classroom discussion about cell characteristics, the functions of life, and exceptions to the current cell theory. In the discussion be open to the ideas of others, remembering that this is a key characteristic of a successful scientist.

CHALLENGE YOURSELF

- 14 On a sheet of paper produce a series of drawings that represent how two membranes could have come to exist on mitochondria and chloroplasts through an engulfing process involving endocytosis.

Biology is concerned not only with life, but also anything that affects life. When studying organisms, it is possible to take two approaches. One approach, often referred to as reductionism, reduces the complex phenomena of organisms to the interaction of their parts. Essentially, this viewpoint says it is the sum of the parts that make up the complex system, the organism. Another approach is that of holism or of looking at systems. This approach has the central belief that the whole is greater than the sum of its parts. Discuss how both approaches have allowed the accumulation of the body of knowledge we now possess in biology. Attempt to utilize both approaches to explain the functions of life as demonstrated by a single cell.

NATURE OF SCIENCE

Serendipity and scientific discoveries: the discovery of cyclins was accidental.

TOK

Another organism, *Elysia chlorotica*, demonstrates a similar situation. *Elysia* is a slug found in salt and tidal marshes and creeks. Its early stage of life, referred to as its juvenile stage, characteristically involves movement and it derives its nutrition by ingesting nutrients from its surroundings. During this juvenile stage it is brown. As it develops, if *Elysia* comes into contact with a specific type of green algae, it will enter its adult phase, in which chloroplasts from the ingested algae will be retained in its digestive tract. The adult stage of *Elysia* is therefore green in colour. The symbiotic relationship between *Elysia* and the green algae allows the adult form of *Elysia* to take on a more sedentary lifestyle, depending on light being available to carry out photosynthesis.

The final bit of evidence for endosymbiotic theory is DNA. DNA provides a code made up of 64 different 'words'. Interestingly, this code has the same meaning in nearly all organisms on Earth and is said to be 'universal'. There are only slight variations, which can be explained by changes since the common origin of life on our planet. As mentioned above, the mitochondria of eukaryotic cells have a DNA code that more closely resembles bacteria than eukaryotic cells. Most scientists believe that the more DNA two organisms have in common, the more closely related they are to one another.

Exercises

- 19 Why did bacteria grow in the broth of the flask that was left open by Pasteur?
- 20 Provide an explanation for how a nucleus might have come to exist within eukaryotic cells.
- 21 How does the example of *Hatena* and the alga represent an emergent explanation of life?
- 22 From the evidence presented in this section, explain why many scientists feel there has been an unbroken chain of life from the first cells on Earth to all cells in organisms alive today.

1.6 Cell division

Understandings:

- Mitosis is division of the nucleus into two genetically identical daughter nuclei.
- Chromosomes condense by supercoiling during mitosis.
- Cytokinesis occurs after mitosis and is different in plant and animal cells.
- Interphase is a very active phase of the cell cycle with many processes occurring in the nucleus and cytoplasm.
- Cyclins are involved in the control of the cell cycle.
- Mutagens, oncogenes, and metastasis are involved in the development of primary and secondary tumours.

Applications and skills:

- Application: The correlation between smoking and incidence of cancers.
- Skill: Identification of phases of mitosis in cells viewed with a microscope or in a micrograph.
- Skill: Determination of a mitotic index from a micrograph.

Guidance

- The sequence of events in the four phases of mitosis should be known.
- Preparation of temporary mounts of root squashes is recommended but phases in mitosis can also be viewed using permanent slides.
- To avoid confusion in terminology, teachers are encouraged to refer to the two parts of a chromosome as sister chromatids, while they are attached to each other by a centromere in the early stages of mitosis. From anaphase onwards, when sister chromatids have separated to form individual structures, they should be referred to as chromosomes.

The cell cycle

The cell cycle describes the behaviour of cells as they grow and divide. In most cases, the cell produces two cells that are genetically identical to the original. These are called daughter cells. The cell cycle integrates a growth phase with a divisional phase. Sometimes, cells multiply so rapidly that they may form a solid mass of cells called a tumour. We refer to this disease state as cancer. It appears that any cell can lose its usual orderly pattern of division, because we have found cancer in almost all tissues and organs.

You may wonder what causes a cell to go out of control. To answer this question, we must first understand the ordinary cell cycle. Usually, the life of a cell involves two major phases. In one phase, growth is the major process. In the other phase, division is the major process. The cell cycle begins and ends as one cell, so it can be represented by a circle divided into various named sections, as shown in Figure 1.26.

Interphase

The largest phase of the cell cycle in most cells is interphase. This is the longest and most variable of the cell-cycle phases. Interphase includes three smaller phases: G_1 , S, and G_2 . During G_1 , the major event is growth of the cell. At the beginning of G_1 , the cell is the smallest it will ever be. After G_1 comes the S phase, in which the main activity is replication of the DNA of the cell, the chromosomes. This phase is sometimes referred to as the synthesis phase. Once the chromosomes have been replicated, the cell enters its second growth phase, called G_2 . During this phase, the cell grows and makes preparations for mitosis, the M phase. During G_2 , organelles may increase in number, DNA begins to condense from chromatin to chromosomes, and microtubules may begin to form.

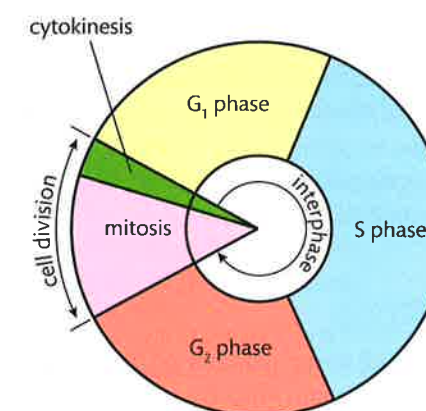


Figure 1.26 The cell cycle in eukaryotes.

Interphase is a very active period in a cell's life. It involves metabolic reactions, DNA replication, and an increase in the number of organelles. Because interphase involves growth, it is essential that protein synthesis occurs at a rapid rate during this phase.

NATURE OF SCIENCE

Tim Hunt and Joan Ruderman were studying gene expression in early embryos. While doing so they found three proteins that varied in concentrations at different times of the cell cycle. These were eventually called cyclins. This illustrates that scientists must always be observant, to spot unplanned and surprising discoveries. This example of 'accidental' discovery is common in science.

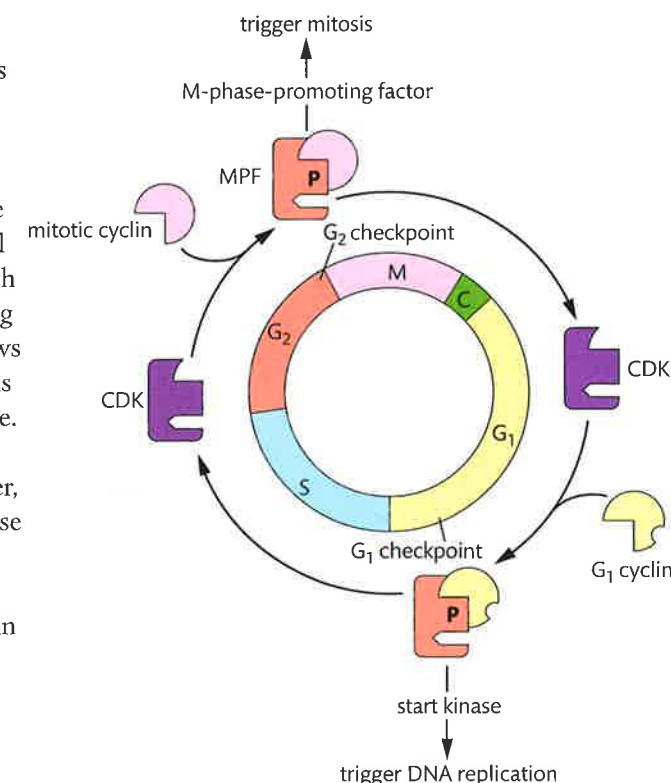


Figure 1.27 Two cyclins are extremely important to the cell cycle: G_1 cyclin and mitotic cyclin. Note their location in the cell cycle and that they must combine with a CDK to become active.

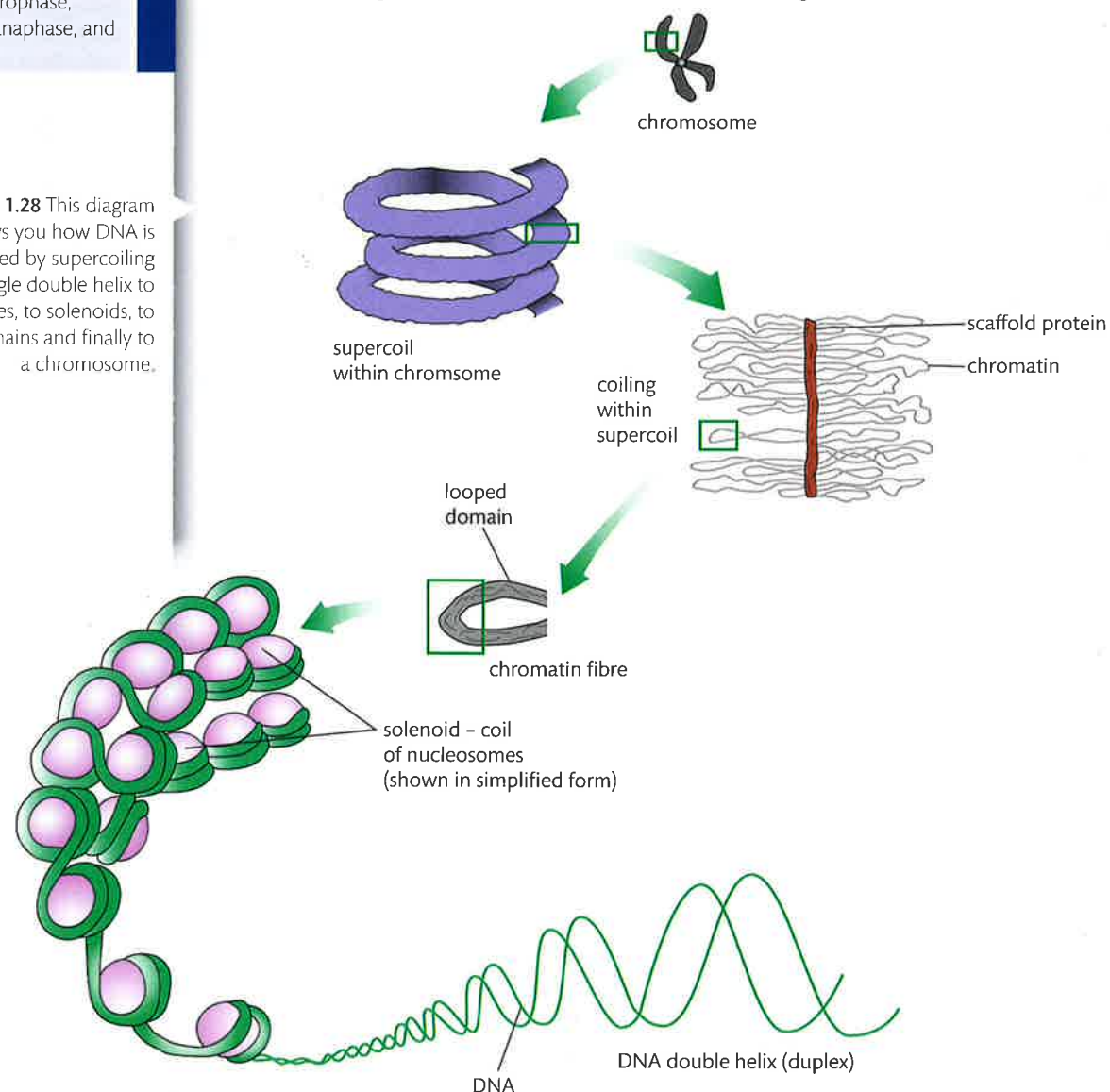
Cyclins are a group of proteins that control the cell's progression through the cell cycle. The cyclins bind to cyclin-dependent protein kinases (CDKs), enabling them to act as enzymes. These activated enzymes then cause the cell to move from G_1 to the S phase and from G_2 to the M phase. The points where the cyclin-activated CDKs function are called checkpoints in the cell cycle. Some cells will pause during G_1 and enter a separate phase, the G_0 phase. G_0 is a non-growing state and certain cells stay in G_0 for varying periods of time. Some cells, such as nerve and muscle cells, never progress beyond the G_0 phase.

Mitosis

Once all the preparatory processes have taken place, and the DNA has replicated, the cell moves into mitosis or the M phase. During mitosis the replicated chromosomes separate and move to opposite poles of the cell, thus providing the same genetic material at each of these locations. When the chromosomes are at the poles of the cell, the cytoplasm divides to form two cells distinct from the larger parent. These two cells have the same genetic material and are referred to as daughter cells.

To remember the correct order of phases in the cell cycle and mitosis, remember the word 'shipmate'. If you take away the word 'she', you get 'ipmat': these letters give you the order of interphase, prophase, metaphase, anaphase, and telophase.

Figure 1.28 This diagram shows you how DNA is packaged by supercoiling from a single double helix to nucleosomes, to solenoids, to looped domains and finally to a chromosome.



Mitosis involves four phases. They are, in sequence:

- prophase
- metaphase
- anaphase
- telophase.

Before considering a detailed description of these phases, it is essential you understand the chromosome. As you will recall, during the second growth phase, G_2 , the chromatin (elongated DNA and histones) begins to condense. This condensation is accomplished via a process called supercoiling. First, the DNA wraps around histones to produce nucleosomes. The nucleosomes are further wrapped into a solenoid. Solenoids group together in looped domains, and then a final coiling occurs to produce the chromosome.

Eukaryotic cells contain chromosomes that, before replication in the S phase of the cell cycle, are composed of one molecule of DNA. After replication, the chromosome includes two molecules of DNA. These two identical molecules are held together by the centromere, and each molecule is referred to as a chromatid. Together, they are called sister chromatids. The chromatids will eventually separate during the process of mitosis. When they do, each is then called a chromosome and each has its own centromere.

Once you are familiar with the structure of a chromosome, you can understand the four phases of mitosis. Remember, when a cell enters the phases of mitosis, replication of DNA has already occurred. Therefore, the chromosomes at this stage are each composed of two sister chromatids.

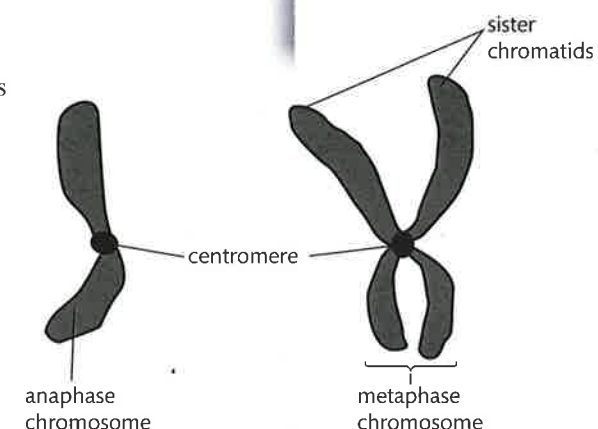


Figure 1.29 An anaphase chromosome is a single molecule of DNA and has a centromere. A metaphase chromosome has sister chromatids attached at the centromere.

Prophase

Examine the figure below.

- 1 The chromatin fibres become more tightly coiled to form chromosomes.
- 2 The nuclear envelope disintegrates and nucleoli disappear.
- 3 The mitotic spindle begins to form and is complete at the end of prophase.
- 4 The centromere of each chromosome has a region called the kinetochore that attaches to the spindle.
- 5 The centrosomes move towards the opposite poles of the cell as a result of lengthening microtubules.

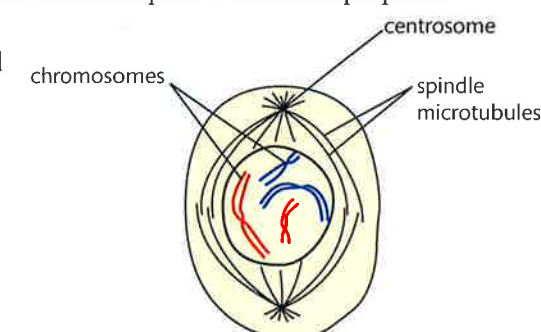


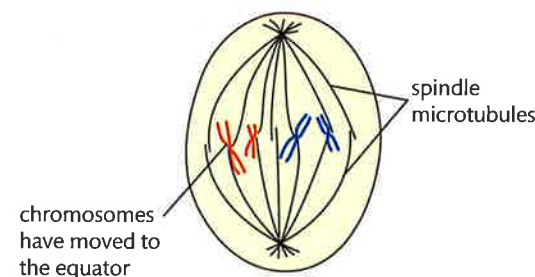
Figure 1.30 This animal cell is in prophase. For clarity, only a small number of chromosomes is shown.

Metaphase

Examine the figure below.

- 1 The chromosomes move to the middle or equator of the cell. This is referred to as the metaphase plate.
- 2 The chromosomes' centromeres lie on the plate.
- 3 The movement of chromosomes arises as the result of the action of the spindle, which is made of microtubules.

Figure 1.31 The cell is now in metaphase. Again, only a small number of chromosomes is shown.



Anaphase

Examine the figure below.

- 1 This is usually the shortest phase of mitosis. It begins when the two sister chromatids of each chromosome are split.
- 2 These chromatids, now chromosomes, move towards the opposite poles of the cell.
- 3 The chromatid movement arises as a result of the shortening of the microtubules of the spindle.
- 4 Because the centromeres are attached to the microtubules, they move towards the poles first.
- 5 At the end of this phase, each pole of the cell has a complete, identical set of chromosomes.

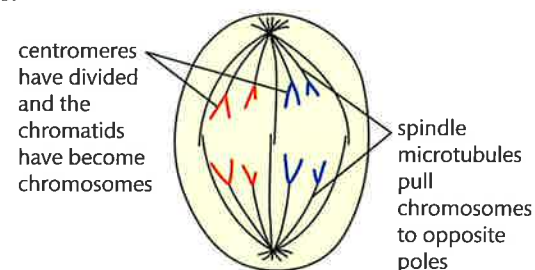


Figure 1.32 The cell is now in anaphase. Again, only a small number of chromosomes is shown.

Telophase

Examine the figure below.

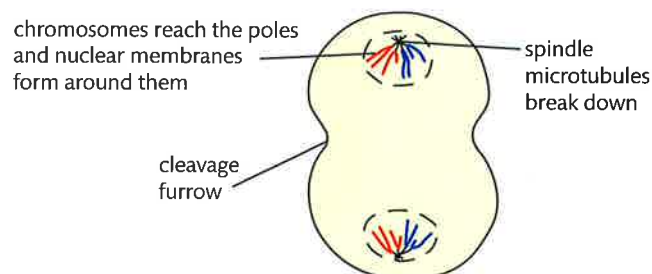


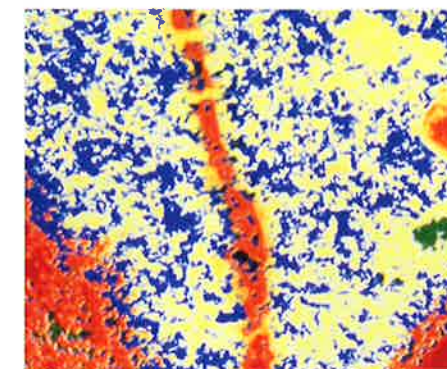
Figure 1.33 Finally, the cell enters telophase.

- 3 The chromosomes start to elongate to form chromatin.
- 4 Nucleoli reappear.
- 5 The spindle apparatus disappears.
- 6 The cell is elongated and ready for cytokinesis.

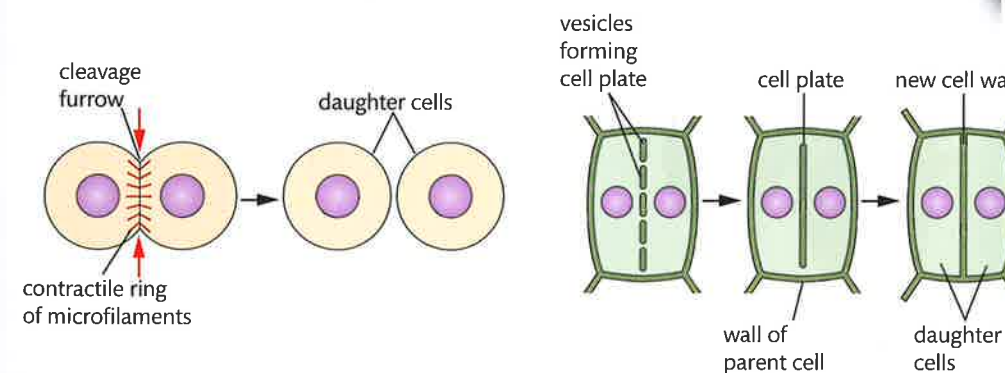
Cytokinesis

As you can see, the phases of mitosis involve nuclear division. It appears that the process of mitosis occurs in discrete stages. But this is not in fact true: the stages occur along a continuum. We only use the separate stages to help us understand the overall process.

Once nuclear division has occurred, the cell undergoes cytokinesis. Cytokinesis in animal cells involves an inward pinching of the fluid plasma membrane to form cleavage furrows. However, plant cells have a relatively firm cell wall and they form a cell plate. The cell plate occurs midway between the two poles of the cell and moves outwards towards the sides of the cell from a central region. Both processes result in two separate daughter cells that have genetically identical nuclei.



Left:
Frog embryo showing cells dividing to form the 4-cell stage.
Right:
Micrograph showing the telophase stage of mitosis in the root tip cell of maize. Most noticeable is the cell wall being formed that will separate the daughter cells in cytokinesis.



Cleavage of an animal cell (SEM)

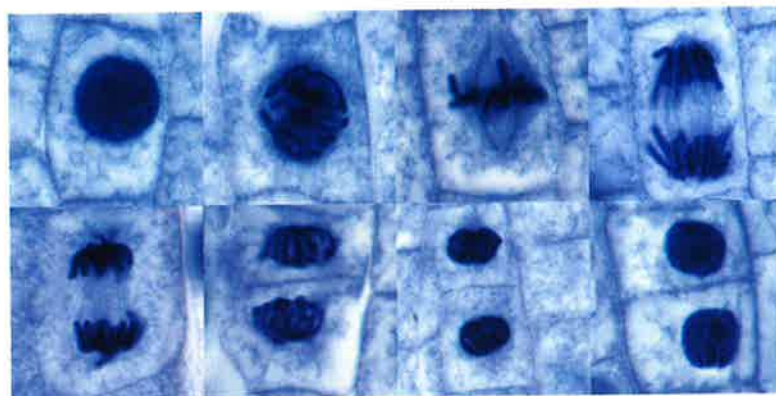
The growth of organisms, development of embryos, tissue repair, and asexual reproduction all involve mitosis. Mitosis does not happen by itself. It is a part of the cell cycle.

Study the micrographs on page 46 to note the main events of the stages of mitosis and to note the differences between plant and animal cells in mitosis. Note that A is from a plant cell and B is from an animal cell.

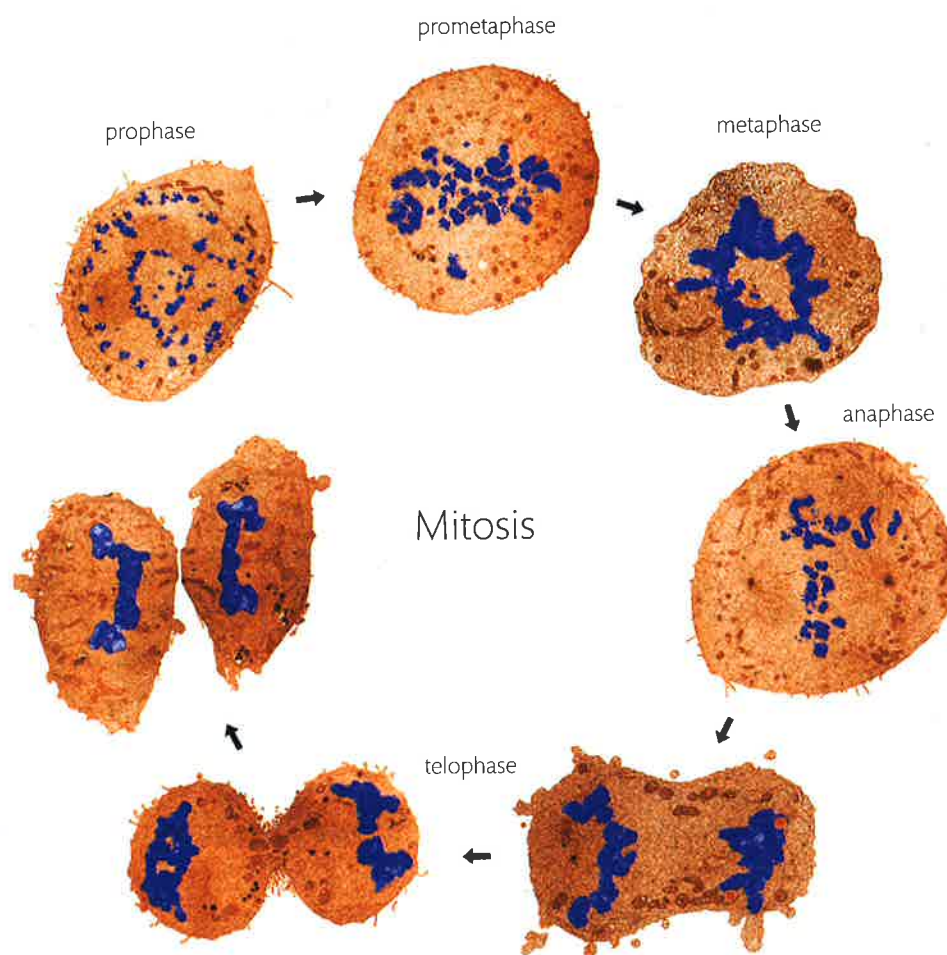
Cell plate formation in a plant cell (TEM)

Figure 1.34 Cytokinesis in animal and plant cells.

A Micrograph of root tip cells from an onion undergoing mitosis. From top left to bottom right: the chromosomes condense and appear as long thread-like structures (prophase). They then align along the centre of the cell (metaphase). Each chromosome consists of two identical sister chromatids that separate and are pulled to opposite ends of the cell (anaphase). Nuclear membranes then form around the two daughter nuclei as the chromosomes de-condense (telophase). The cell then divides (cytokinesis).



B Composite of transmission electron micrographs showing the stages of mitosis in a human lymphocyte.



Laboratories all over the world are busy researching causes and treatments for all known types of cancers. Sharing of information is a common occurrence amongst these laboratories and their researchers.

Cancer

As mentioned earlier, cancer occurs when a cell's cycle becomes out of control. The result is a mass of abnormal cells referred to as a tumour. A primary tumour is one that occurs at the original site of a cancer. A secondary tumour is a metastasis, a cancerous tumour that has spread from the original location to another part of the organism. An example of metastasis is a brain tumour that is in fact composed of breast cancer cells. In some cases the metastasis of the primary tumour cells is so extensive that secondary tumours are found in many locations within the organism.

The mitotic index is an important tool for predicting the response of cancer cells to chemotherapy. It is the ratio of the number of cells in a tumour or tissue type undergoing mitosis compared with the number of cells not undergoing mitosis. A higher mitotic index indicates a more rapid proliferation of cells of a certain type. It is likely that tumours with higher mitotic indices will be more difficult to control, and a patient with such a tumour may be given a poorer prognosis than a patient with a tumour that has a lower mitotic index.

A question to consider here is how or why a primary tumour forms. Most organisms have sections of genes that may mutate or may be expressed at abnormally high levels. These sections of genes, called oncogenes, contribute to converting a normal cell into a cancer cell. The oncogenes may start to change or go through mutation because they are triggered by an outside agent referred to as a mutagen. One such potential mutagen is cigarette smoke. There is a correlation between smoking and the incidence of cancer. This has been shown consistently in many independent studies. Examine the graph from the World Health Organization below and note the positive correlation.

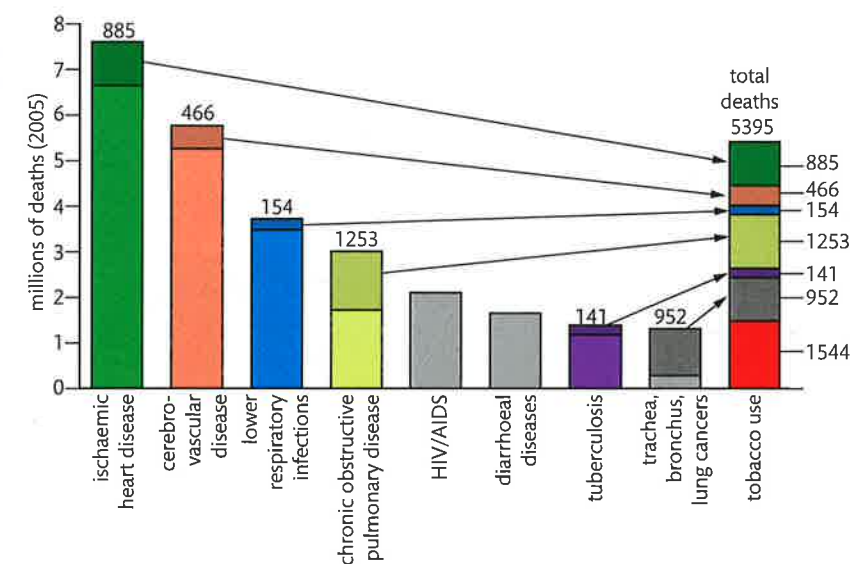


Figure 1.35 Examine this graph from the World Health Organization noting tobacco use as a risk factor for eight leading causes of death in the world. Especially note the information provided concerning trachea, bronchus, and lung cancers. Darker areas indicate proportions of deaths that are related to tobacco use and are coloured according to the column of the respective cause of death. WHO, <http://www.who.int/tobacco/mpower/graphs/en/index.html>

A very interesting activity is to find micrographs on the internet of various human tissues going through cell division. Determine the mitotic index of these various types of tissue. Attempt to find micrographs of the same types of tissue that are cancerous and determine their mitotic index. This comparison will show quite effectively the more rapid cell division found in cancer tissues.

CHALLENGE YOURSELF

Cancer cells have a higher rate of mitotic division than normal cells. Because of this, cancer tissue has a higher mitotic index than normal tissue. This is why cancer cells can grow and spread very rapidly.

- If a microscopic field of 1000 normal cells has 900 cells in interphase, estimate the number of cells in interphase when 1000 cells of the same type are from tissue that is cancerous.
- If the normal cells have an average cell cycle time of 600 minutes, estimate the average, relative cell cycle time of the cancer cells.
- How does this information affect the mitotic index of the two sets of cells?

TOK

This is an appropriate time to discuss the unethical actions of the tobacco industry in the suppression of results linking smoking with cancer. A global perspective should be included in this discussion.

To learn more about the mitotic phases, go to the hotlinks site, search for the title or ISBN, and click on Chapter 1: Section 1.6.

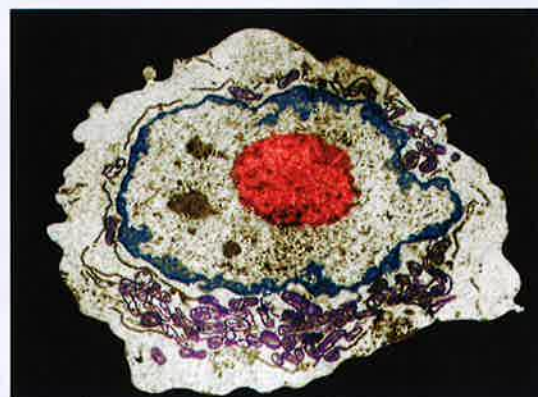


Exercises

- 23** A chemical called colchicine disrupts the formation of microtubules. What effect would this drug have on a cell going through mitosis?
- 24** If a parent cell has 24 chromosomes, how many chromatids would be present during metaphase of mitosis?
- 25** Explain when cytokinesis occurs within the cell cycle.
- 26** Compare cytokinesis in plant and animal cells.
- 27** What is the value of the mitotic index?

Practice questions

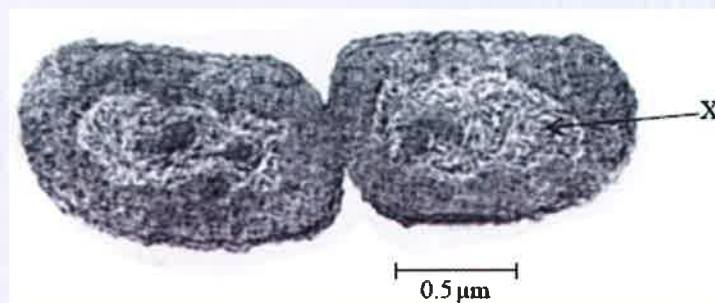
- 1** The micrograph below shows an adult human stem cell.
- (a)** The cell cycle can be divided into two parts: interphase and mitosis.
- (i)** Identify, with a reason, whether the stem cell in the micrograph is in interphase or mitosis. (1)
- (ii)** Deduce **two** processes that occur in human cells during this part of the cell cycle, but not during the other part. (2)
- (b)** State **two** characteristics of stem cells that can be used to distinguish them from other body cells. (2)
- (c)** Outline **one** therapeutic use of stem cells. (3)
- (Total 8 marks)



- 2** Below is a micrograph of an *E. coli* bacterium undergoing reproduction. In the diagram what does label X identify?

- A** Nucleoid region **B** Chromatin **C** Histones **D** Endoplasmic reticulum

(Total 1 mark)



www.bio.mtu.edu/campbell/prokaryo.htm

- 3** Which of the following is **not** a function performed by a membrane protein?

- A** Hormone-binding sites **B** Cell adhesion **C** Enzyme synthesis **D** Pumps for active transport
- (Total 1 mark)

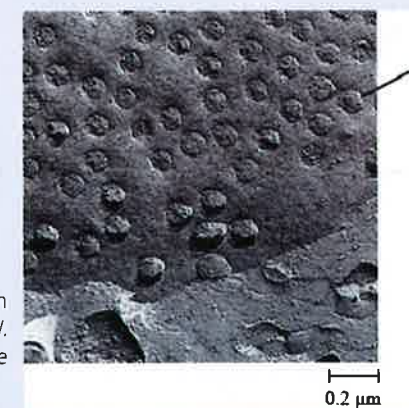
- 4** Which of the following take(s) place during either interphase or mitosis in animal cells?

- I. Re-formation of nuclear membranes
II. Pairing of homologous chromosomes
III. DNA replication

- A** I only **B** I and II only **C** II and III only **D** I and III only
- (Total 1 mark)

- 5 (a)** The scanning electron micrograph below shows the surface of the nuclear envelope with numerous nuclear pores.

- (i)** Calculate the power of magnification of the image. (1)
- (ii)** State the diameter of the pore labelled X. (1)
- (b)** List **two** examples of how human life depends on mitosis. (1)
- (c)** Describe the importance of stem cells in differentiation. (3)
- (Total 6 marks)



Adapted from Nelson and Cox 2000, © Don W. Fawcett/ Science Source