# IB STUDY GUIDES

# Biology

## FOR THE IB DIPLOMA

### Standard and Higher Level

Andrew Allott

**OXFORD**

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# Introduction and acknowledgements

The IB Biology Programme continues to evolve, in response to developments in research and changes in the perceived importance of different topics. This book is intended to help students find the information that they need quickly and easily and allow time for thinking about the issues involved. It follows the programme being taught from 2007 that will be examined from 2009 onwards.

All topics needed for Higher Level (HL) and Standard Level (SL) Biology are covered, including all eight options. The topics covered are in the same sequence as in the syllabus, but within some topics the sequence of sub-topics has been slightly altered, to give a more coherent progression of ideas. An index of assessment statements in the syllabus has been included to show where each one is covered.

- Topics 1–6 are core topics studied at both HL and SL.
- Topics 7–11 are additional topics studied only at HL.
- Options A–C are studied only at SL (each student takes two of the eight options).
- Options D–G can be studied at HL or SL, with extra material needed at HL, separated on clearly marked pages at the end of the option.
- Option H is studied only at HL.

Practice questions are included at the end of topics. Most of these are taken, with permission, from past IB examination papers. Answers to each question are given, though students and teachers may be able to find other valid answers!

Guidance is given for students working on internal assessment, extended essays or preparing for final exams.

There has never been a more important time to study biology. There are unprecedented opportunities for using recently developed techniques in beneficial ways, but there are also greater threats to the natural world than for millions of years. A thorough understanding of the principles of biology is essential if we are to counter the threats and make the most of the opportunities. Biology teachers worldwide should continue to be commended for the work they do in promoting this understanding. Teachers of IB Biology often take on an additional challenge – to promote international understanding. There are many opportunities for this in Biology. Apart from humans, living organisms do not recognize national frontiers. Living organisms throughout the biosphere, including humans, are interdependent. Human activities have international impacts, so international co-operation is essential to protect the biosphere and its treasure-house of biodiversity.

# CONTENTS

*(Italics denote Higher level pages)*

# ORIGIN OF INDIVIDUAL QUESTIONS

The questions detailed below are all taken from past IB examination papers. The questions are from May (M) or November (N), Sample, 1998 (98), 1999 (99) and 2000 (00) paper 2 (P2) or paper 3 (P3) with question number in brackets. All other questions are IB style questions written by the author of this book.

**TOPICS 1 AND 2 STATISTICAL ANALYSIS AND CELLS**
1. MOOSLP2(1)    2. M99SLP2(1)

**TOPIC 3 THE CHEMISTRY OF LIFE**
3. N99SLP2(3)

**TOPIC 4 GENETICS**
1. SAMPLE HLP2(3)    2. MOOSLP2(2)

**TOPIC 5 ECOLOGY AND EVOLUTION**
1. M99SLP2(1)    2. M98HLP2(3)

**TOPIC 6 HUMAN HEALTH AND PHYSIOLOGY**
1. N99SLP2(1)    2. N99SLP2(2)

**TOPIC 7 NUCLEIC ACIDS AND PROTEINS**
3. N98HLP2(3)

**TOPIC 8 CELL RESPIRATION AND PHOTOSYNTHESIS**
1. N98SLP3(C1)    2. N99SLP3(C2)

**TOPIC 9 PLANT SCIENCE**
3. M98SLP3(C1)

**TOPIC 10 GENETICS**
1. M99HLP2(3)    2. N98HLP2(2)

**TOPIC 11 HUMAN HEALTH AND PHYSIOLOGY**
Questions written by author

**OPTION A – HUMAN NUTRITION AND HEALTH**
Questions written by author

**OPTION B – PHYSIOLOGY OF EXERCISE**
1. N98SLP3(B1)

**OPTION C – CELLS AND ENERGY**
1. SAMPLE SLP3(C1)    2. M98SLP3(C2)

**OPTION D – EVOLUTION**
1. M98HLP3(D1)    3. N98HLP3(D2)

**OPTION E – NEUROBIOLOGY AND BEHAVIOUR**
1. M99HLP3(E2)    2. N99SLP3(E2)

**OPTION F – MICROBES AND BIOTECHNOLOGY**
Questions written by author

**OPTION G – ECOLOGY AND CONSERVATION**
1. N00SLP3(G1)    2. M98SLP3(G3)

**OPTION H – FURTHER HUMAN PHYSIOLOGY**
2. N99HLP3(H2)

# Mean and standard deviation

There is almost always variation in biological data. The amount of variation can be shown using a graph called a frequency distribution. Most variation gives a bell-shaped frequency distribution called the **normal distribution**. The mean value is in the middle of the distribution. The **mean** of a set of values is calculated by dividing the sum of the values by the number of values.

For example, the sum of the values 7, 9, 11 and 17 is 44 and as there are four values, the mean is 44 divided by 4, which is 11. The **standard deviation** is used to assess how far the values are spread above and below the mean. It is calculated by entering data into a graphic display or scientific calculator and pressing the standard deviation function key. A high standard deviation shows that the data are widely spread, whereas a low standard deviation shows that the data are clustered closely around the mean.

The standard deviation can be used to help decide whether the difference between two means is likely to be significant. Two examples are described below.

## LEFT AND RIGHT HAND LENGTHS

Thirty teenage boys measured the length of their left and right hands, to find out whether they are different. Individual boys' left and right hand length varied by as much as 10mm. The results are shown in the frequency distribution below.

| Hand | Mean length | Standard deviation |
|------|-------------|--------------------|
| left | 188.6 mm | 11.0 mm |
| right | 188.4 mm | 10.9 mm |
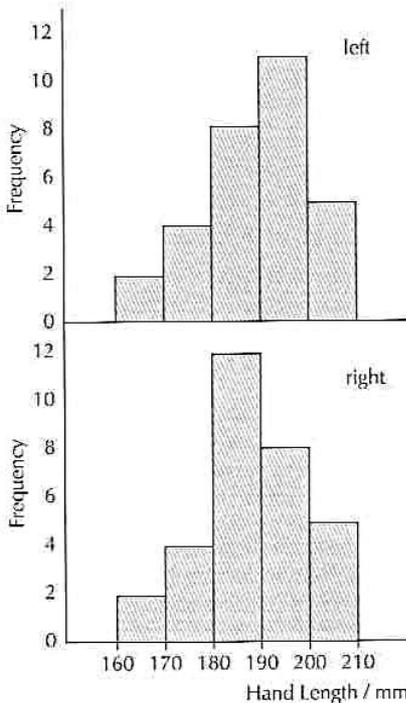


Because the standard deviations are much greater than the difference in mean length, it is very unlikely that the difference in mean length between left and right hands is significant.

## The normal distribution



68% of the area is between −1.0 and +1.0 standard deviations.

More than 95% of the area is between −2.0 and +2.0 standard deviations.
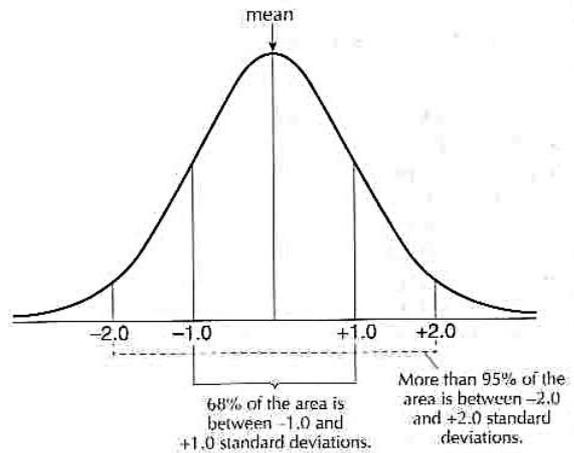
A useful rule is that 68% of the values lie within one standard deviation of the mean in a normal distribution and approximately 95% of the values lie within two standard deviations of the mean (above).

## ERROR BARS

Bars on graphs extending above and below the mean value are used to show the variability of the data. They may show the range of the data, or the standard deviation.

## HAND AND FOOT LENGTHS

The same thirty teenage boys who measured their hand lengths also measured the length of their right foot, to find out whether it was different from their hand lengths. The results are shown in the frequency distribution below.

| Hand/foot | Mean length | Standard deviation |
|-----------|-------------|--------------------|
| right hand | 188.4 mm | 10.9 mm |
| right foot | 262.5 mm | 14.3 mm |
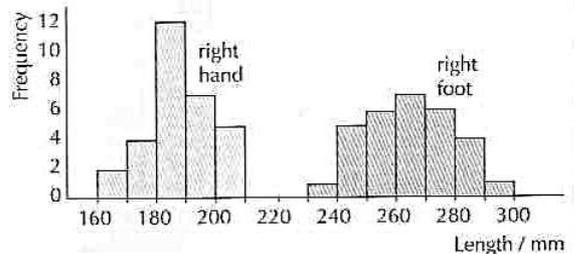


Because the standard deviations are much less than the difference in mean length, it is very likely that the difference in mean length between right hands and right feet is significant.

# Relationships – significance and cause

## THE t-TEST

On the previous page, sizes of standard deviations were used to assess whether differences between means were likely to be significant. Biologists often need to decide more objectively whether differences between means are significant. One of the most frequently used methods is called the t-test.

**The t-test can be used to find out whether there is a significant difference between the means of two populations.** A difference is considered statistically significant if the probability of it being due to random variation is 5% or less. t is a statistic that is calculated from the two sets of measurements. The larger the difference between the two means, the larger t is. The larger the standard deviations, the smaller t is. It is not necessary to learn how to calculate t, because a graphic display calculator or computer is nearly always now used.

### Stages in using the t-test

1. Enter the values in a graphic display calculator or a spreadsheet program, with values for the two populations entered separately.
2. Use the calculator function keys or computer software to calculate t.
3. Find the number of degrees of freedom. This will be the total number of values in both populations, minus two.
4. Find the critical value for t either using computer software or a table of values of t. The level of significance (P) chosen should be 0.05 (5%) and the appropriate row should be selected according to the number of degrees of freedom.
5. Compare the calculated value of t with the critical value. If the critical value is exceeded, there is evidence of a significant difference between the means, at the 5% level.

### Table of critical values of t

| | | Level of significance (P) | | | | |
|---|---|---|---|---|---|---|
| | 0.2 | 0.1 | 0.05 | 0.02 | 0.01 | 0.002 |
| 1 | 3.078 | 6.314 | 12.706 | 31.821 | 83.657 | 318.310 |
| 2 | 1.886 | 2.920 | 4.303 | 6.985 | 9.925 | 27.327 |
| 3 | 1.638 | 2.353 | 3.182 | 4.541 | 5.841 | 10.215 |
| 4 | 1.533 | 2.132 | 2.776 | 3.747 | 4.604 | 7.173 |
| 5 | 1.476 | 2.015 | 2.571 | 3.365 | 4.032 | 5.893 |
| 6 | 1.440 | 1.943 | 2.447 | 3.143 | 3.707 | 5.208 |
| 7 | 1.415 | 1.895 | 2.385 | 2.998 | 3.499 | 4.785 |
| 8 | 1.397 | 1.860 | 2.308 | 2.896 | 3.355 | 4.501 |
| 9 | 1.383 | 1.833 | 2.262 | 2.821 | 3.250 | 4.297 |
| 10 | 1.372 | 1.812 | 2.228 | 2.764 | 3.169 | 4.144 |
| 11 | 1.363 | 1.796 | 2.201 | 2.718 | 3.106 | 4.025 |
| 12 | 1.356 | 1.782 | 2.179 | 2.681 | 3.055 | 3.930 |
| 13 | 1.350 | 1.771 | 2.180 | 2.650 | 3.012 | 3.852 |
| 14 | 1.345 | 1.761 | 2.145 | 2.624 | 2.977 | 3.787 |
| 15 | 1.341 | 1.753 | 2.131 | 2.602 | 2.947 | 3.733 |
| 16 | 1.337 | 1.746 | 2.120 | 2.583 | 2.921 | 3.686 |
| 17 | 1.333 | 1.740 | 2.110 | 2.567 | 2.898 | 3.646 |
| 18 | 1.330 | 1.734 | 2.101 | 2.552 | 2.878 | 3.610 |
| 19 | 1.328 | 1.729 | 2.093 | 2.539 | 2.861 | 3.579 |
| 20 | 1.325 | 1.725 | 2.086 | 2.528 | 2.845 | 3.552 |
| 30 | 1.310 | 1.697 | 2.042 | 2.457 | 2.750 | 3.385 |
| 40 | 1.303 | 1.684 | 2.021 | 2.423 | 2.704 | 3.307 |

*Degrees of freedom* (left axis label)

### Examples of the use of the t-test

These examples are based on the data for hand and foot lengths described on the previous page.

1. Testing the difference between mean lengths of left and right hands

    Mean length of left hands = 188.6mm
    Mean length of right hands = 188.4mm
    $t = 0.082$
    Critical value for $t = 2.002$ ($P = 0.05$)

The calculated value of t is much smaller than the critical value, so the difference between the mean lengths of left and right hands is not significant.

2. Testing the difference between the mean lengths of right hands and right feet.

    Mean length of right hands = 188.4mm
    Mean length of right feet = 262.5mm
    $t = 23.3$
    Critical value for $t = 2.005$ ($P = 0.05$)

The calculated value of t is much larger than the critical value, showing that the difference between the mean lengths of hands and feet is significant.

In these two examples, the t-test confirms conclusions that are reasonably obvious. In biological research, it is often much less clear whether differences between means are significant and the t-test is therefore very useful.

## CORRELATION AND CAUSE

The scattergraph below shows that there is a positive correlation between the lengths of the right hand and right feet of thirty teenage boys – boys with larger hands tend to have larger feet as well.
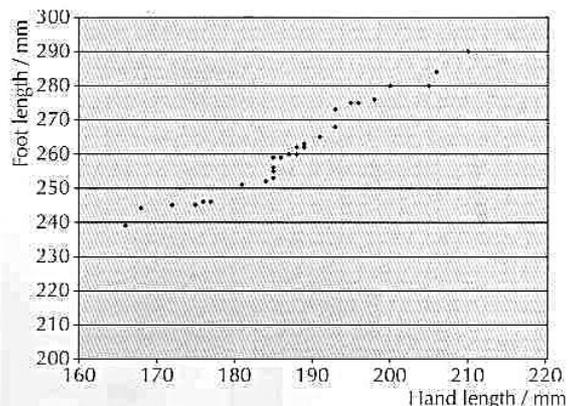
Although there is a positive correlation between hand and foot length, we know that increases in the length of the hand do not cause increases in length of the foot. Instead, both are due to the factors that control growth in teenage boys. This mistake is often made in analysis of data – a correlation between two variables is assumed to show that there is a causal link. It is important to remember that correlation is not proof of cause.

# Cell theory

## INTRODUCING CELLS

Cells consist of **cytoplasm**, enclosed in a **plasma membrane**, usually controlled by a single **nucleus**. Two cell types that can be easily looked at under a light microscope are human cheek cells, scraped from inside the mouth (left) and moss leaf cells (right).

**Human cheek cell**
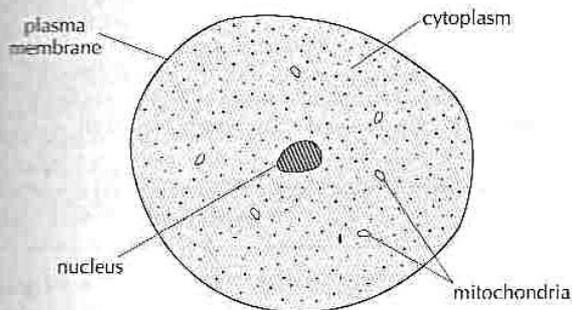


**Moss leaf cell**
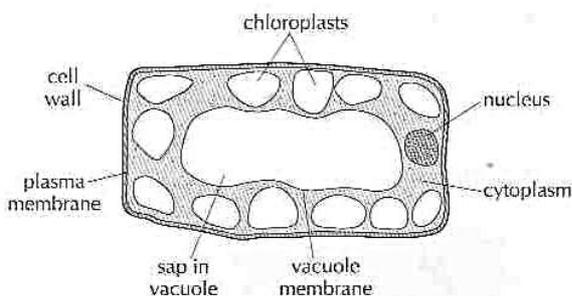


## UNICELLULAR ORGANISMS

Some organisms such as *Amoeba* (below), *Chlorella* and *Euglena* have only one cell. This single cell has to carry out all the functions of life:

metabolism – chemical reactions inside the cell
response – reacting to stimuli
homeostasis – controlling conditions inside the cell
growth – increasing in size
reproduction – producing offspring
nutrition – obtaining food.

*Amoeba*



100 μm

## MULTICELLULAR ORGANISMS

Multicellular organisms consist of many cells. These cells do not have to carry out many different functions. Instead, they can become specialized for one particular function and carry it out very efficiently. Cells in a multicellular organism therefore develop in different ways. This is called **differentiation**. The way in which this occurs is described on page 4. Multicellular organisms are said to show **emergent properties**. This means that the whole organism is more than the sum of its parts, because of the complex interactions between cells.

## THE CELL THEORY

The cell theory includes these statements:
• living organisms are composed of cells
• cells are the smallest units of life
• cells come from pre-existing cells.

Many organisms have been examined and have been found to consist of cells, but there are some cases where the idea of living organisms consisting of tiny box-like structures does not seem to fit. For example, skeletal muscle is made up of **muscle fibres**. These are much larger than most cells (300 or more mm long) and contain hundreds of nuclei. Most fungi consist of thread-like structures called **hyphae**, which in some species contain many nuclei without dividing walls between. Many tissues, such as bone, contain a greater volume of **extracellular material** (material outside the cell membrane) than of cells. Despite these awkward cases, most living tissues are composed of cells. Also, whereas cells taken from an organism often survive for a time, smaller parts of an organism do not. Cells do therefore seem to be the smallest units of life that are capable of survival.

There is also evidence for the third part of the cell theory. Some of the classic experiments in biology showed that spontaneous generation of life is impossible (below). The first cells must have been formed in the origin of life from non-cellular material, but today there is no evidence that cells can be formed except by cell division.



Sterilized soup in an open container decays because bacteria float in

Sterilized soup in a sealed container does not decay as no bacteria are present

# Stem cells and differentiation

## DIFFERENTIATION

Cells in a multicellular organism develop in different ways and can therefore carry out different functions. This is called **differentiation**. The cells need different genes to develop in different ways. Each cell has all of these genes, so could develop in any way, but it only uses the ones that it needs to follow its pathway of development. Once a pathway of development has begun in a cell, it is usually fixed and the cell cannot change to follow a different pathway. The cell is said to be committed. The drawings (below) show three of the hundreds of different types of differentiated cells in humans.

### Heart muscle tissue



20 μm

All heart muscle cells contain structures made from protein fibres that are used to contract the cell and help to pump blood in the heart.
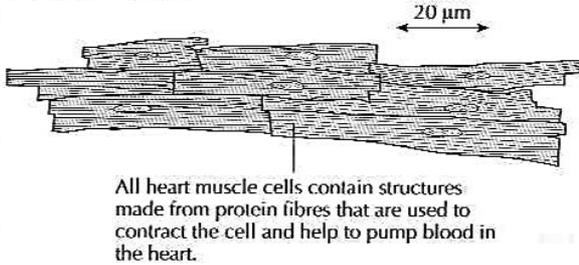
### Sensory neuron



### Beta cell in the pancreatic islets



vesicles of insulin
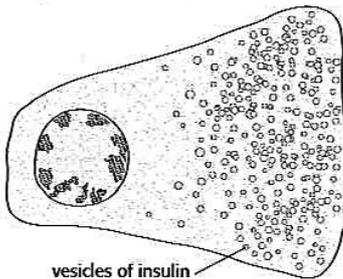
## STEM CELLS

Stem cells are defined as cells that have the capacity to self-renew by cell division and to differentiate. Human embryos consist entirely of stem cells in their early stages, but gradually the cells in the embryo commit themselves to a pattern of differentiation. Once committed, a cell may still divide several more times, but all of the cells formed will differentiate in the same way and so they are no longer stem cells.

Small numbers of embryonic cells remain as stem cells however and they are still present in the adult body. They are found in most human tissues, including bone marrow, skin and liver. They give some human tissues considerable powers of regeneration and repair. The stem cells in other tissues only allow limited repair – brain, kidney and heart, for example. There has been great interest in stem cells because of their potential for tissue repair and for treating a variety of degenerative conditions. For example, Parkinson's disease, multiple sclerosis and strokes all involve the loss of neurons or other cells in the nervous system. Although still only at the research stage, there is the potential to use stem cells to replace them.

## THERAPEUTIC USE OF STEM CELLS

In the future, many therapies may involve the use of stem cells. Some therapeutic uses have already been introduced. One example is given here.

1. The placenta and umbilical cord of a baby is used as a source of stem cells. At the end of childbirth, the placenta is taken and placed on a stand, with the umbilical cord hanging down from it. Blood drains out of the umbilical cord and is collected – about 100cm$^3$. The cord blood contains many hematopoietic stem cells. These cells can divide and differentiate into any type of blood cell.



placenta

umbilical cord

shelf
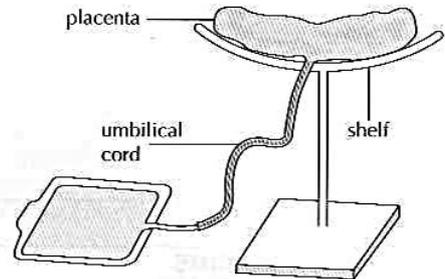
2. Red blood cells are removed from the cord blood and the remaining fluid is then tested to find its tissue type, checked for disease-causing organisms and stored in liquid nitrogen, in a special bank of cord blood.



3. Cord blood can be used to treat patients, especially children, who have developed certain forms of leukemia. This is a cancer in which the cells in bone marrow divide uncontrollably, producing far too many white blood cells. The patient's tissue type is matched with cord blood in the bank. If suitable cord blood is available, the patient is given chemotherapy drugs that kill bone marrow cells, including the cells causing the leukemia.



transfusion of cord blood
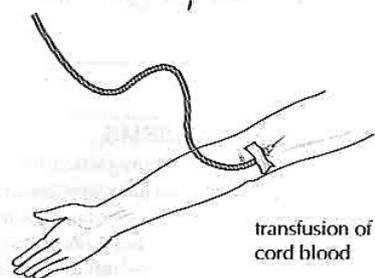
4. The selected cord blood is taken from the bank, thawed and introduced into the patient's blood system, usually via a vein in the chest or arm. The hematopoietic stem cells establish themselves in the patient's bone marrow, where they divide repeatedly to build up a population of bone marrow cells to replace those killed by the chemotherapy drugs.

# Size in cell biology

## LIMITATIONS TO CELL SIZE
Cells do not carry on growing indefinitely. They reach a maximum size and then may divide.
If a cell became too large, it would develop problems because its surface area to volume ratio would become too small.
As the size of any object is increased, the ratio between the surface area and the volume decreases. Consider the surface area to volume ratio of cubes of varying size as an example.
The rate at which materials enter or leave a cell depends on the surface area of the cell.
However, the rate at which materials are used or produced depends on the volume. A cell that becomes too large may not be able to take in essential materials or excrete waste substances quickly enough.
The same principle works for heat. Cells that generate heat may not be able to lose it quickly enough if they grow very large.
Surface area to volume ratios are important in biology. They help to explain many phenomena apart from maximum cell sizes.

## UNITS FOR SIZE MEASUREMENTS
Most S.I. units differ from each other by a factor of 1000.
One millimetre is a thousand times smaller than 1 metre.
One micrometre is a thousand times smaller than 1 millimetre.
One nanometre is a thousand times smaller than 1 micrometre.
The most useful units for measuring the sizes of cells and structures within them are nanometres (nm) and micrometres (μm).
The typical sizes of some important structures in biology are shown opposite.

## CALCULATING MAGNIFICATION
Photographs or drawings of structures seen under the microscope show them larger than they really are – they magnify them. It is useful to know how much larger the image is than the actual specimen. This factor is called the magnification. It is always helpful to show the magnification on a drawing of a biological structure.
Follow these instructions to calculate magnification.
1. Choose an obvious length, for example the maximum diameter of a cell. Measure it on the drawing.
2. Measure the same length on the actual specimen.
3. If the units used for the two measurements are different, convert one of them into the same units as the other one.
4. Divide the length on the drawing by the length on the actual specimen. The result is the magnification.

$$\text{Magnification} = \frac{\text{size of image}}{\text{size of specimen}}$$

This equation can also be used to calculate the actual size of a specimen if the magnification and size of the image are known.

## SCALE BARS
A scale bar is a line added to a micrograph or a drawing to help to show the actual size of the structures.
For example, a 10 μm bar shows how large a 10 μm object would appear.
The figure below shows is a scanning electron micrograph of a leaf with the magnification and a scale bar both shown.

**Scanning electron micrograph of leaf (× 480)**



| Scale | Structure |
|---|---|
| 10mm | |
| 1mm | |
| 100 μm | cells of eukaryotes |
| 10μm | organelles |
| 1μm | bacteria (sizes vary) |
| 100 nm | viruses (sizes vary) |
| 10 nm | Thickness of cell membranes |
| 1 nm | molecules (e.g. DNA molecule is 2nm in diameter) |
| 0.1 nm | |

1000 mm = 1 m

1000 μm = 1 mm
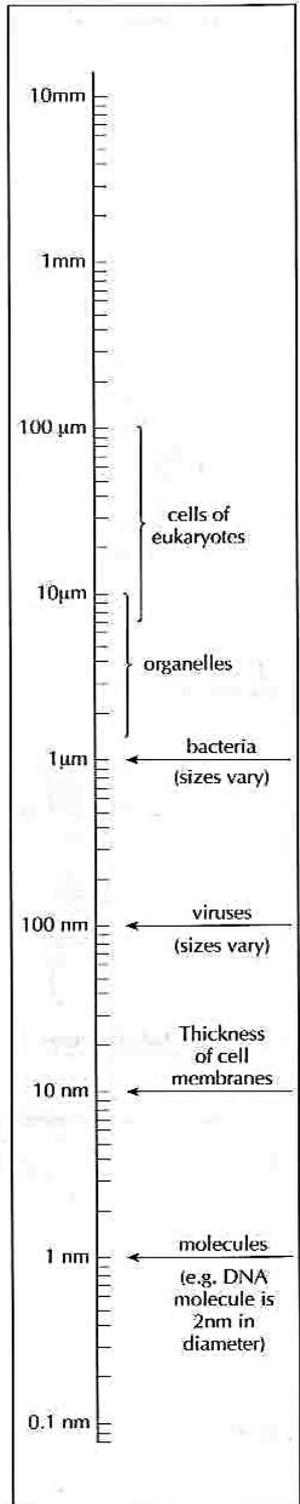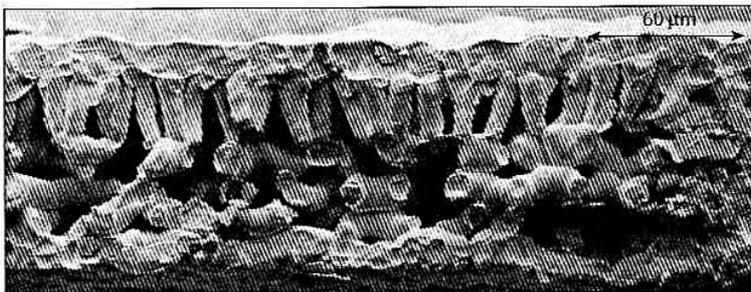
1000 nm = 1 μm

# Prokaryotic cells

## ULTRASTRUCTURE OF CELLS

From the 1950s onwards, cell structure could be studied in much greater detail than before, using electron microscopes. What was revealed is called the ultrastructure of the cell.

Cells were divided into two types according to their structure, **prokaryotic** and **eukaryotic**. The first cells to evolve were prokaryotic and many organisms still have prokaryotic cells, including all bacteria. These cells have no nucleus and the name prokaryotic means *before the nucleus*.

The functions of structures within prokaryotic cells are shown (right). Prokaryotic cells divide in two by a process called **binary fission**.

## FUNCTIONS OF PARTS OF A PROKARYOTIC CELL

| Structure | Function |
|---|---|
| Cell wall | Forms a protective outer layer that prevents damage from outside and also bursting if internal pressure is high. |
| Plasma membrane | Controls entry and exit of substances, pumping some of them in by active transport. |
| Cytoplasm | Contains enzymes that catalyse the chemical reactions of metabolism and contains DNA in a region called the nucleoid. |
| Pili | Hair-like structures projecting from the cell wall, that can be ratcheted in and out; when connected to another bacterial cell they can be used to pull cells together. |
| Flagella | Solid protein structures, with a corkscrew shape, projecting from the cell wall, which rotate and cause locomotion. |
| Ribosomes | Small granular structures that synthesise proteins by translating messenger RNA. Some proteins stay in the cell and others are secreted. |
| Nucleoid | Region of the cytoplasm that contains naked DNA, which is the genetic information of the cell. |

Electron micrograph of *Escherichia coli* (1–2 μm in length)
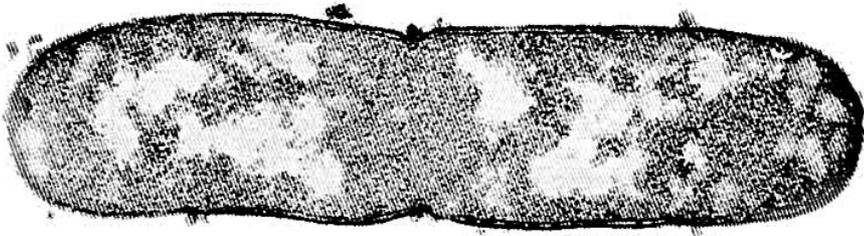


Drawing to help interpret the electron micrograph



ribosomes   cell wall   plasma membrane   cytoplasm   nucleoid (region containing naked DNA)
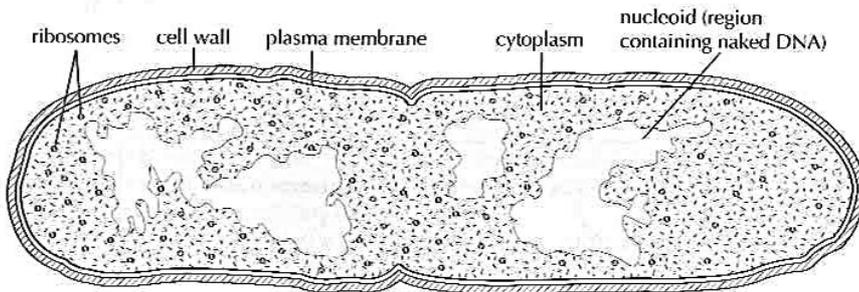
Electron micrograph of *Escherichia coli* showing surface features



pili

flagellum
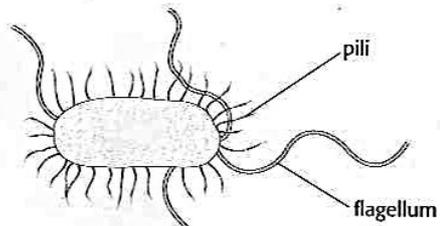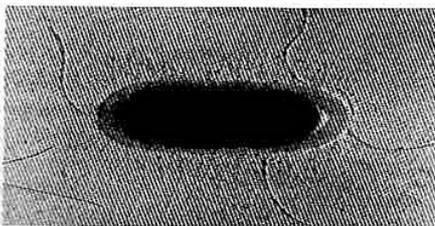
# Eukaryotic cells

## STRUCTURE OF A EUKARYOTIC CELL

Electron micrograph of a liver cell (× 6000)
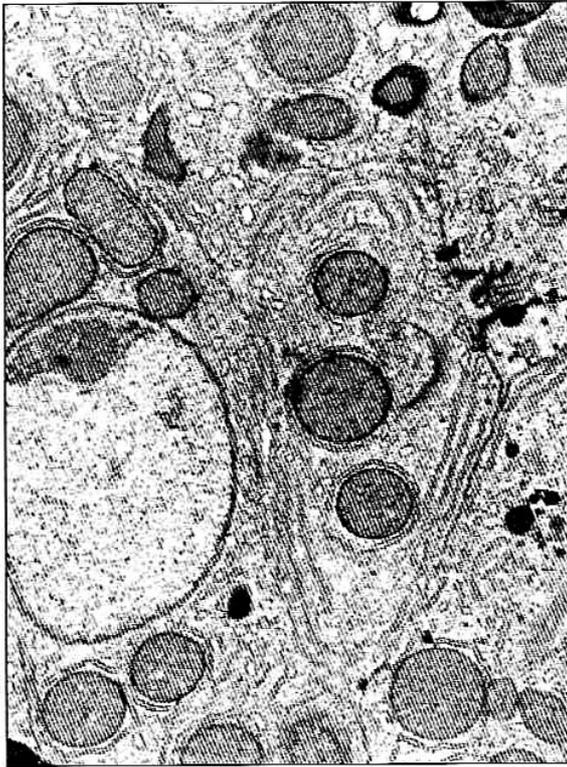
Drawing to interpret parts of the electron micrograph



Labels: Golgi apparatus, plasma membrane, free ribosomes, rough endoplasmic reticulum, lysosome, mitochondrion, nucleus
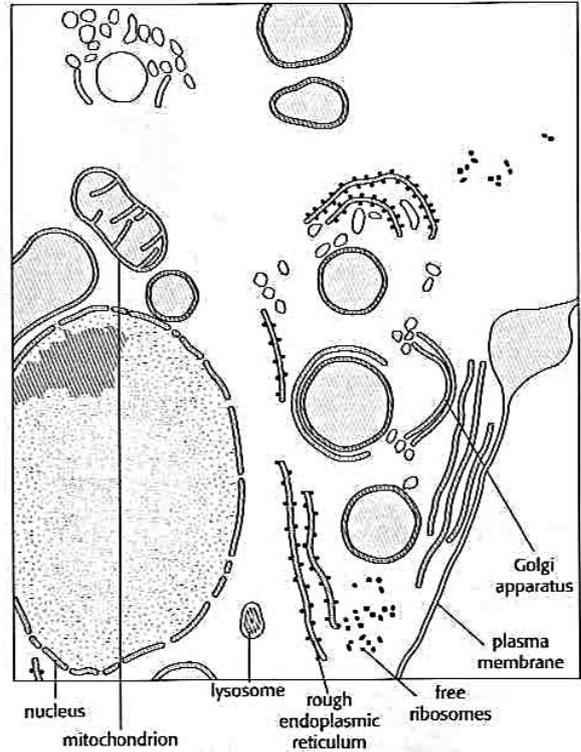
## COMPARING PROKARYOTIC AND EUKARYOTIC CELLS

| Feature | Prokaryotic cells | Eukaryotic cells |
|---|---|---|
| Type of genetic material | A naked loop of DNA | Chromosomes consisting of strands of DNA associated with protein. Four or more chromosomes are present. |
| Location of genetic material | In the cytoplasm in a region called the nucleoid | In the nucleus inside a double nuclear membrane called the nuclear envelope |
| Mitochondria | Not present | Always present |
| Ribosomes | Small sized – 70S | Larger sized – 80S |
|  |  | (S = Svedberg units – related to the size of organelles) |
| Internal membranes | Few or none are present | Many internal membranes that compartmentalize the cytoplasm including ER, Golgi apparatuses, lysosomes |

## COMPARING PLANT AND ANIMAL CELLS

| Feature | Animal | Plant |
|---|---|---|
| Cell wall | No cell wall, only a plasma membrane | Cell wall *and* plasma membrane present |
| Chloroplasts | Not present | Present in cells that photosynthesize |
| Polysaccharides | Glycogen is used as a storage compound | Starch is used as a storage compound |
| Vacuole | Not usually present | Large fluid-filled vacuole often present |
| Shape | Able to change shape. Usually rounded | Fixed shape. Usually rather regular |

# Membrane structure and membrane proteins

## Fluid mosaic model of a biological membrane

hydrophilic phosphate head · hydrophobic hydrocarbon tail · glycoprotein · cholesterol

phospholipid bilayer

integral proteins embedded in the phospholipid bilayer

peripheral protein on the surface of the membrane
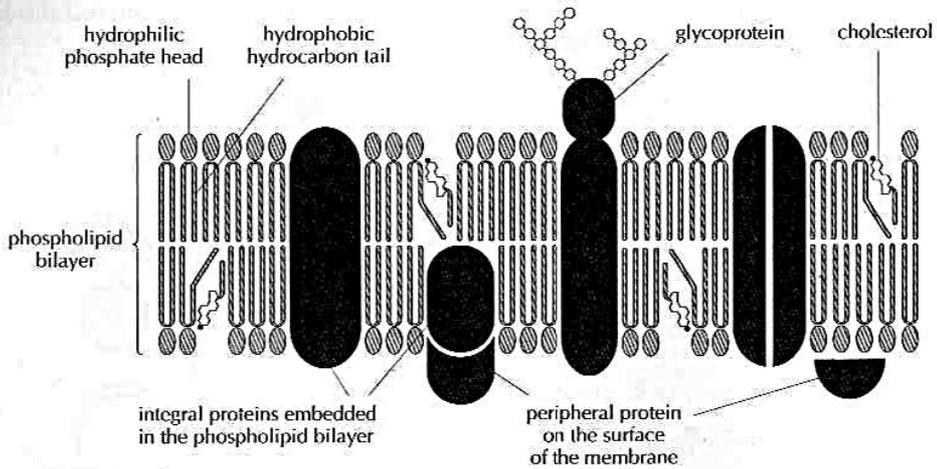
## PHOSPHOLIPIDS

Hydrophilic molecules are attracted to water. Hydrophobic molecules are not attracted to water, but are attracted to each other. Phospholipid molecules are unusual because they are partly hydrophilic and partly hydrophobic.

The phosphate head is hydrophilic and the two hydrocarbon tails are hydrophobic. In water, phospholipids form double layers with the hydrophilic heads in contact with water on both sides and the hydrophobic tails away from water in the centre. This arrangement is found in biological membranes. The attraction between the hydrophobic tails in the centre and between the hydrophilic heads and the surrounding water makes membranes very stable.

## FLUIDITY OF MEMBRANES

Phospholipids in membranes are in a fluid state. This allows membranes to change shape in a way that would be impossible if they were solid. The fluidity also allows vesicles to be pinched off from membranes or fuse with them.

## MEMBRANE PROTEINS

Some electron micrographs show the positions of proteins within membranes. The proteins are seen to be dotted over the membrane. This gives the membrane the appearance of a mosaic. Because the protein molecules float in the fluid phospholipid bilayer, biological membranes are called fluid mosaics. The figure (above) is a diagram showing the fluid mosaic model of a biological membrane. Some of the functions of membrane proteins are shown below.

## Functions of membrane proteins

HORMONE BINDING SITES · ENZYMES · ELECTRON CARRIERS · CHANNELS FOR PASSIVE TRANSPORT · PUMPS FOR ACTIVE TRANSPORT

OUTSIDE

INSIDE

ATP

ADP + P

OUTSIDE

INSIDE

A site exposed on the outside of the membrane allows one specific hormone to bind. A signal is then transmitted to the inside of the cell

Enzymes located in membranes either catalyse reactions inside or outside the cell, depending on whether the active site is on the inner or outer surface

Electron carriers are arranged in chains in the membrane so that electrons can pass from one carrier to another

Channels are passages through the centre of membrane proteins. Each channel allows one specific substance to pass through

Pumps release energy from ATP and use it to move specific substances across the membrane

# Passive transport across membranes

## DIFFUSION

Solids, liquids and gases consist of particles – atoms, ions and molecules. In liquids and gases, these particles are in continual motion. The direction that they move in is random. If particles are evenly spread then their movement in all directions is even and there is no net movement – they remain evenly spread despite continually moving. Sometimes particles are unevenly spread – there is a higher concentration in one region than another. This causes diffusion.

*Diffusion is the passive movement of particles from a region of higher concentration to a region of lower concentration, as a result of the random motion of particles.*

Diffusion occurs because more particles move from the region of higher concentration to the region of lower concentration than move in the opposite direction. Diffusion can occur across membranes if there is a concentration gradient and if the membrane is permeable to the particle. For example, membranes are freely permeable to oxygen, so if there is a lower concentration of oxygen inside a cell than outside, it will diffuse into the cell. Membranes are not permeable to cellulose, so it does not diffuse across, even if there is a higher concentration on one side of a membrane than the other.

## SIMPLE AND FACILITATED DIFFUSION

Membranes allow some substances to diffuse through but not others – they are **partially permeable**. Some of these substances move between the phospholipid molecules in the membrane – this is **simple diffusion**. Other substances are unable to pass between the phospholipids. To allow these substances to diffuse through membranes, channel proteins are needed. This is called **facilitated diffusion**. Channel proteins are specific – they only allow one type of substance to pass through. For example, chloride channels only allow chloride ions to pass through. Cells can control whether substances pass through their plasma membranes by facilitated diffusion, by the types of channel protein that are produced and inserted into the membrane. Cells cannot control the direction of movement. Facilitated diffusion always causes particles to move from a region of higher concentration to a region of lower concentration. Both simple and facilitated diffusion are passive processes – no energy has to be used by the cell to make them occur.
There are sodium and potassium channel proteins in the membranes of neurones that open and close, depending on the voltage across the membrane. They are called voltage-gated channels and are used during the transmission of nerve impulses.



membrane consisting of phospholipid bilayer

higher concentration    lower concentration

membrane containing channel proteins

Solute unable to diffuse through membrane    Solute able to diffuse through membrane    Facilitated diffusion through membrane containing channel proteins
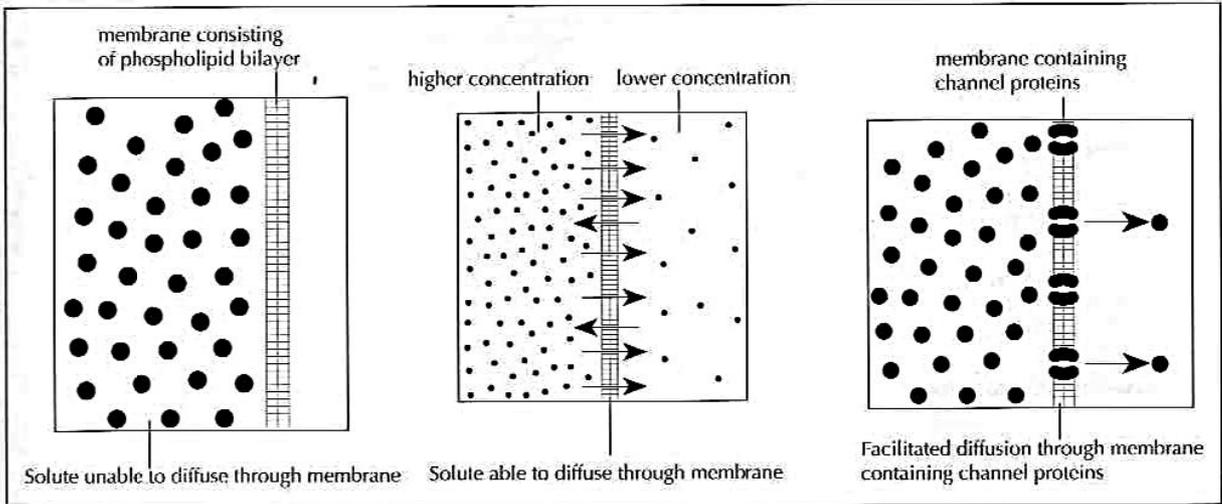
## OSMOSIS

Plasma membranes are usually freely permeable to water. The passive movement of water across membranes is different from diffusion across membranes, because water is the solvent. A **solvent** is a liquid in which particles dissolve. Dissolved particles are called **solutes**. The direction in which water moves is due to the concentration of solutes, rather than the concentration of water molecules, so it is called osmosis, rather than diffusion.

*Osmosis is the passive movement of water molecules from a region of lower solute concentration to a region of higher solute concentration, across a partially permeable membrane.*

Attractions between solute particles and water molecules are the reason for water moving to regions with a higher solute concentration.



Solute molecules cannot diffuse out as the membrane is impermeable to them

region of lower solute concentration (in this case pure water)

partially permeable membrane

region of higher solute concentration
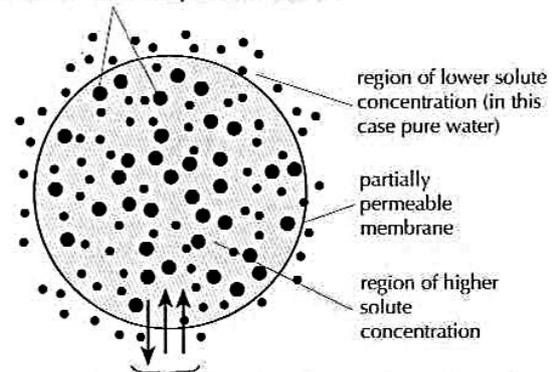
Water molecules move in and out through the membrane but more move in than out. There is a net movement from the region of lower solute concentration to the region of higher solute concentration

# Active transport across membranes

## PUMP PROTEINS AND ACTIVE TRANSPORT

Active transport is the movement of substances across membranes using energy from ATP. Active transport can move substances against the concentration gradient – from a region of lower to a region of higher concentration. Protein pumps in the membrane are used for active transport. Each pump only transports particular substances, so cells can control what is absorbed and what is expelled. Pumps work in a specific direction – the substance can only enter the pump on one side and can only exit on the other side.
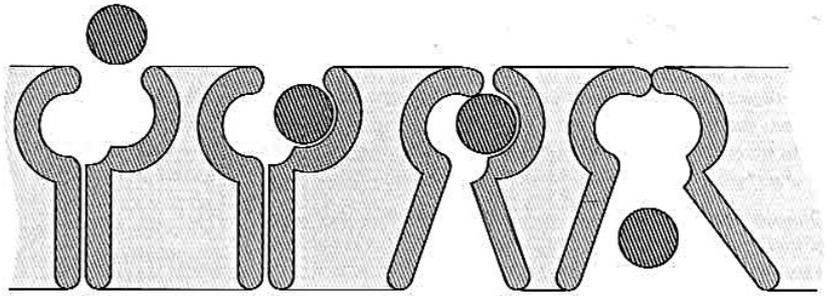
Particle enters the pump from the side with a lower concentration

Particle binds to a specific site. Other types of particle cannot bind

Energy from ATP is used to change the shape of the pump

Particle is released on the side with a higher concentration and the pump then returns to its original shape

## TRANSPORT OF MATERIALS BY VESICLES IN THE CYTOPLASM

Proteins are synthesized by ribosomes and then enter the rough endoplasmic reticulum

Vesicles bud off from the rER and carry the proteins to the Golgi apparatus

The Golgi apparatus modifies the proteins

Vesicles bud off from the Golgi apparatus and carry the modified proteins to the plasma membrane

### ENDOCYTOSIS

Part of the plasma membrane is pulled inwards

A droplet of fluid becomes enclosed when a vesicle is pinched off

Vesicles can then move through the cytoplasm carrying their contents

### EXOCYTOSIS

Vesicles fuse with the plasma membrane

The contents of the vesicle are expelled

The membrane then flattens out again

## EXTRACELLULAR COMPONENTS

The plasma membrane is the barrier that separates a cell from its surroundings. Cells sometimes produce components and then place them outside the plasma membrane, using exocytosis. These are called extracellular components. Two examples of the roles of extracellular components are outlined here:

Cytoplasm containing **intracellular** components

plasma membrane

Structures outside the membrane are **extracellular**
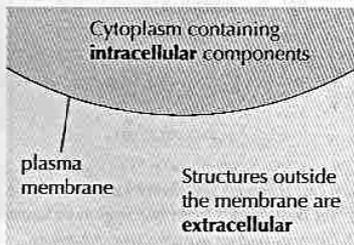
### 1. The plant cell wall

Plants construct their cell walls by synthesising cellulose fibres in vesicles and adding them to the inner surface of the cell wall. Other substances are secreted to interconnect the cellulose fibres. The strength of the cellulose allows plant cell walls to have these roles:
- maintaining the cell's shape
- allowing high pressure to build up in the cell without it bursting
- high pressure in plant cells prevents excessive water uptake by osmosis
- high pressure in plant cells (turgor pressure) makes the cell almost rigid, helping to support the plant.

### 2. Glycoproteins

Many animal cells secrete glycoproteins, consisting of a protein to which carbohydrate is attached. This forms an extracellular matrix. Tissues that consist of a single layer of cells produce a thin layer of extracellular matrix called the basement membrane, for example around blood capillaries and around alveoli in the lungs. The matrix is a gel and has these roles:
- supporting single layers of thin cells, which might otherwise tear or perforate
- cell to cell adhesion, for example, a basement membrane helps capillary wall cells to adhere to alveolus wall cells.

# Cell division

## THE CELL CYCLE IN EUKARYOTES

New cells are produced by division of existing cells. If many new cells are needed, cells go through a cycle of events again and again. This is called the cell cycle. The longest phase in this cycle is **interphase**. This is a very active period, during which the cell carries out many biochemical reactions and grows larger. The DNA molecules in the chromosomes are uncoiled and the genes on them can be transcribed, allowing the protein synthesis that is needed for growth. There is an increase in the number of mitochondria and in plant cells in the number of chloroplasts. There are three stages in interphase:

$G_1$ – a period of growth, DNA transcription and protein synthesis
**S phase** – the period during which all DNA in the nucleus is replicated
$G_2$ – a period in which the cell prepares for division.

At the end of interphase, the cell begins **mitosis** – the process by which the nucleus divides to form two genetically identical nuclei. Towards the end of mitosis, the cytoplasm of the cell starts to divide and eventually two cells are formed, each containing one nucleus. The process of dividing the cytoplasm to form two cells is **cytokinesis**. The two cells begin interphase when mitosis and cytokinesis have been completed.



## THE PHASES OF MITOSIS



① **Early prophase**

Spindle microtubules are growing

Chromosomes are becoming shorter and fatter by supercoiling

② **Late prophase**

Each chromosome consists of two identical chromatids formed by DNA replication in interphase and held together by a centromere

Spindle microtubules extend from each pole to the equator

The nuclear membrane has broken down and chromosomes have moved to the equator

③ **Metaphase**

Spindle microtubules from both poles are attached to each centromere, on opposite sides

④ **Anaphase**

The centromeres have divided and the chromatids have become chromosomes

Spindle microtubules pull the genetically identical chromosomes to opposite poles

⑤ **Early telophase**

All chromosomes have reached the poles and nuclear membranes form around them

Spindle microtubules break down

Chromosomes uncoil and are no longer individually visible

⑥ **Late telophase**

The cell divides (cytokinesis) to form two cells with genetically identical nuclei

## USES OF MITOSIS

Mitosis is used in eukaryotes whenever genetically identical cells are needed:

- during growth
- during embryonic development, when the large cell produced by fertilization (zygote) divides repeatedly to produce many smaller cells
- when tissues have been damaged and need to be repaired
- to reproduce asexually.

## TUMOUR FORMATION

Sometimes the normal control of mitosis in a cell fails, due to a change in the genes of the cell. This cell divides into two, which inherit the change in the genes. The two daughter cells divide to form four cells. Repeated uncontrolled divisions soon produce a mass of cells called a tumour. This can happen in any tissue and in any organ. Tumours can grow to a large size and can spread to other parts of the body. The diseases caused by the growth of tumours are called cancer.

1  The photomicrograph below shows a transverse section of part of a liver cell.
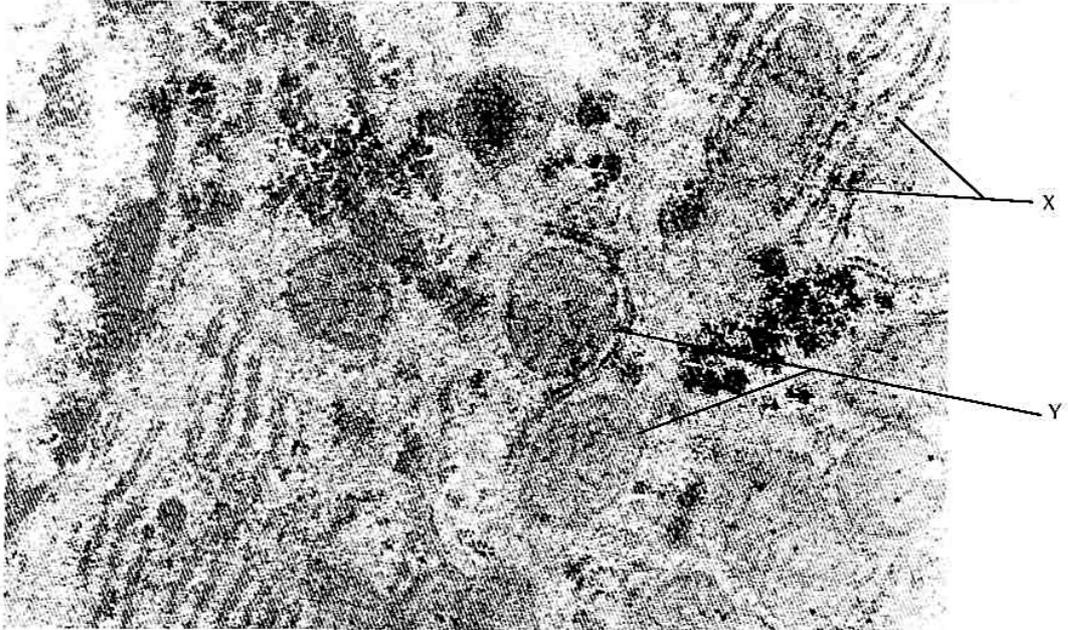


a) Identify the organelles labelled X and Y. . [2]

b) On the photomicrograph, identify the nuclear membrane and show its position with a clear label. [1]

c) The liver cell shown in the photomicrograph was making large amounts of two substances.

Deduce what the two substances were, giving reasons for your answer based on the organelles visible in the photomicrograph. [2]

2  The diagram below represents the fluid model of a cell membrane.
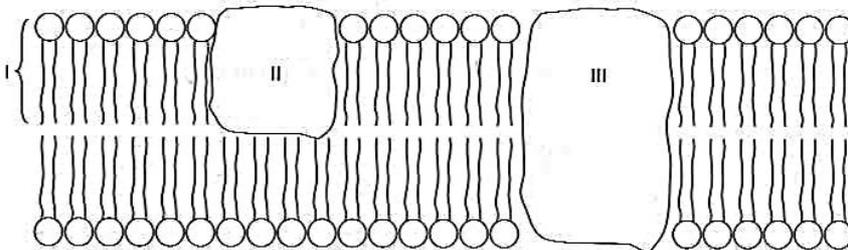


a) (i) State the name of the molecule labelled I. [1]

(ii) Label the diagram to show which part of molecule I is hydrophobic and which part is hydrophilic. [1]

b) (i) Identify whether molecule II is an integral or a peripheral protein. [1]

(ii) Describe the part played by molecule III in active transport. [2]

3  Ten teenage boys, aged 17 or 18, estimated their body fat percentage by measurements of skin fold thickness.

The estimates (%) were: 25.6, 12.9, 8.1, 10.2, 10.0, 8.9, 8.1, 15.3, 11.2, 13.7.

a) (i) Calculate the mean estimated body fat percentage. [2]

(ii) Calculate the standard deviation. [2]

The boys also measured their blood pressure. The boys whose estimated body fat percentages were higher tended to have higher blood pressure.

b) (i) What is this type of relationship between two variables called? [2]

(ii) Discuss whether this relationship proves that becoming obese causes high blood pressure. [2]

# Water

## POLARITY OF WATER

Water molecules consist of two hydrogen atoms bonded to an oxygen atom. The hydrogen atoms have a slight positive charge and the oxygen atom has a slight negative charge. So, water molecules have two poles – a positive hydrogen pole and a negative oxygen pole (below). This feature of a molecule is called **polarity**.

**Water molecule**

Hydrogen pole is slightly positive

Oxygen pole is slightly negative
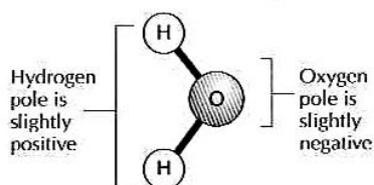
## HYDROGEN BONDING IN WATER

A bond can form between the positive pole of one water molecule and the negative pole of another. This is called a **hydrogen bond**. In liquid water many of these bonds form, giving water properties that make it a very useful substance for living organisms. The diagram (below) shows a hydrogen bond between two water molecules.
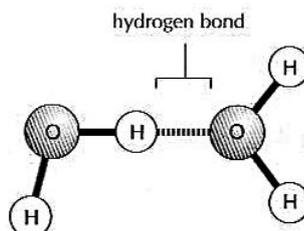
hydrogen bond

## THE PROPERTIES OF WATER

| Name of the property | Outline of the properties of water | Relationship between the properties of water and its uses in living organisms |
| --- | --- | --- |
| **Cohesion** | Water molecules stick to each other because of the hydrogen bonds that form between them. | Strong pulling forces can be exerted to suck columns of water up to the tops of the tallest trees in their transport systems. These columns of water rarely break. Water is used as a **transport medium** in the xylem of plants. |
| **Solvent properties** | Many different substances dissolve in water because of its polarity (below). Inorganic particles with positive or negative charges dissolve, for example sodium ions. Organic substances with polar molecules dissolve, for example glucose. Enzymes also dissolve in water. | Most chemical reactions in living organisms take place with all of the substances involved in the reactions dissolved in water. Water is the **medium for metabolic reactions**. The solvent properties of water allow many substances to be carried dissolved in water in the blood of animals and the sap of plants. Water can be used as a **transport medium**. |
| **Thermal properties: heat capacity** | Water has a large heat capacity – large amounts of energy are needed to raise its temperature. The energy is needed to break some of the hydrogen bonds. | Blood, which is mainly composed of water, can carry heat from warmer parts of the body to cooler parts. Blood is used as a **transport medium** for heat. |
| **Thermal properties: boiling point** | The boiling point of water (100°C) is high, because to change it from a liquid to a gas all of the hydrogen bonds between the water molecules have to be broken. | Water is below boiling point almost everywhere on Earth, and in most areas it is above freezing point. As a liquid, rather than a solid or a gas, it can act as the **medium for metabolic reactions**. |
| **Thermal properties: the cooling effect of evaporation** | Water can evaporate at temperatures below boiling point. Hydrogen bonds have to be broken to do this. The heat energy needed to break the bonds is taken from the liquid water, cooling it down. | Evaporation of water from plant leaves (transpiration) and from the human skin (sweat) has useful cooling effects. Water can be used as a **coolant**. |
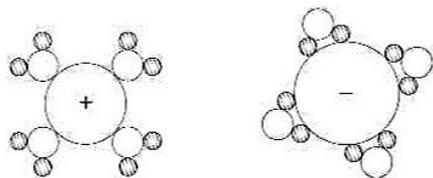
Ions with positive or negative charges dissolve as they are attracted to the negative or positive poles of water molecules.
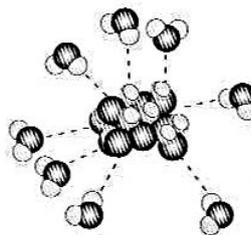
Many molecules are polar so are attracted to water molecules and dissolve.

# Elements and compounds in living organisms

## ELEMENTS IN LIVING ORGANISMS

Living organisms contain many chemical elements, some in large quantities and some in very small amounts. The four commonest chemical elements of life are carbon, hydrogen, oxygen and nitrogen. They are part of all the main organic compounds in living organisms. Examples of other elements that are needed are shown in the table opposite.

## ORGANIC AND INORGANIC COMPOUNDS

Living organisms contain many chemical compounds. Some of them are organic and some are inorganic. Organic compounds are defined as compounds containing carbon that are found in living organisms. There are a few carbon compounds that are inorganic even though they can be found in living organisms. These are all simple carbon compounds that are also widely found in the environment. Carbon dioxide, carbonates and hydrogen carbonates are three examples of inorganic carbon compounds. All compounds that contain no carbon are inorganic. Three types of organic compound are found in large amounts in living organisms – carbohydrates, lipids and proteins.

## SUBUNITS OF ORGANIC MACROMOLECULES

The molecules of many organic compounds are large and so are called macromolecules.
They are built up using small and relatively simple subunits. Some important subunits are shown below.

## CHEMICAL ELEMENTS AND THEIR ROLES

| Element and symbol | Role in plants, animals and prokaryotes |
|---|---|
| Sulphur S | Needed to make two of the twenty amino acids that proteins contain |
| Calcium Ca | Acts as a messenger, binding to calmodulin and other proteins that regulate processes inside cells, including transcription |
| Phosphorus P | Part of the phosphate groups in ATP and DNA molecules |
| Iron Fe | Needed to make cytochromes –proteins used for electron transport during aerobic cell respiration |
| Sodium Na | Pumped into the cytoplasm to raise the solute concentration and cause water to enter by osmosis |

These elements have other specific roles in some organisms. For example, iron is needed to make hemoglobin in many animals and calcium is needed to make the minerals that strengthen bones and teeth.

### Subunits of proteins, carbohydrates and lipids
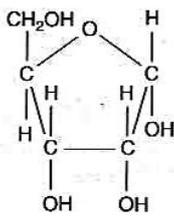
ribose
(a monosaccharide)
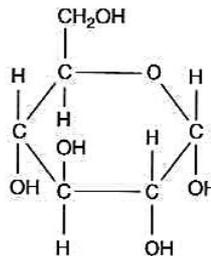
glucose
(a monosaccharide)

$(CH_3)$ —— $(CH_2)_n$ —— C

fatty acids
(general structure)

amino acids
(each of the twenty
amino acids in proteins
has a different R group)
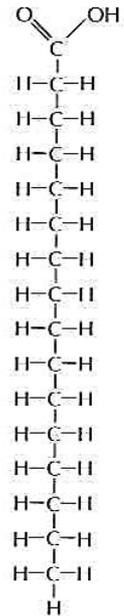
fatty acid
(number of carbon
atoms and bonding
between carbon
atoms varies)

# Building macromolecules

## CONDENSATION REACTIONS

In a condensation reaction two molecules are joined together to form a larger molecule. Water is also formed in the reaction. For example, two amino acids can be joined together to form a dipeptide by a condensation reaction. The new bond formed is a **peptide linkage**.

**Condensation of two amino acids to form a dipeptide and water**
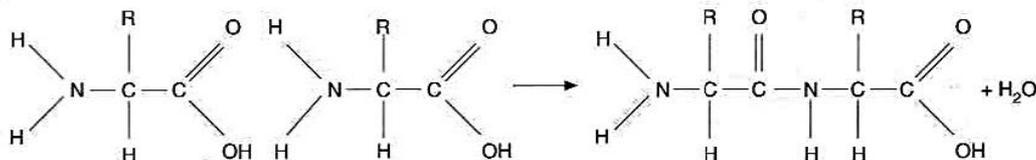


Further condensation reactions can link amino acids to either end of the dipeptide, eventually forming a chain of many amino acids. This is called a **polypeptide**.

In a similar way, condensation reactions can be used to build up carbohydrates and lipids. The basic subunits of carbohydrates are monosaccharides. Two monosaccharides can be linked to form a disaccharide and more monosaccharides can be linked to a disaccharide to form a large molecule called a **polysaccharide**. Fatty acids can be linked to glycerol by condensation reactions to produce lipids called glycerides. A maximum of three fatty acids can be linked to each glycerol, producing a **triglyceride**.

## HYDROLYSIS REACTIONS

Large molecules such as polypeptides, polysaccharides and triglycerides can be broken down into smaller molecules by hydrolysis reactions. Water molecules are used up in hydrolysis reactions. Hydrolysis reactions are the reverse of condensation reactions.

polypeptides + water $\longrightarrow$ dipeptides or amino acids

polysaccharides + water $\longrightarrow$ disaccharides or monosaccharides

glycerides + water $\longrightarrow$ fatty acids + glycerol
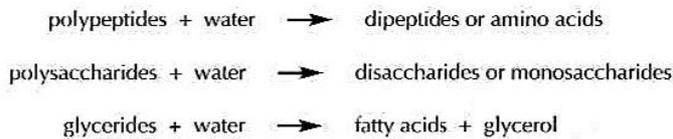
## EXAMPLES OF CARBOHYDRATES

| | Examples | Example of use in animals | Example of use in plants |
|---|---|---|---|
| **Monosaccharides** | glucose galactose fructose | Glucose is carried by the blood to transport energy to cells throughout the body | Fructose is used to make fruits sweet-tasting, attracting animals to disperse seeds in the fruit |
| **Disaccharides** | maltose lactose sucrose | Lactose is the sugar in milk, that provides energy to young mammals until they are weaned | Sucrose is carried by phloem to transport energy to cells throughout the plant |
| **Polysaccharides** | starch glycogen cellulose | Glycogen is used as a short-term energy store in liver and in muscles | Cellulose is used to make strong fibres that are used to construct the plant cell wall |

## FUNCTIONS OF LIPIDS

- **Energy storage** – in the form of fat in humans and oil in plants
- **Heat insulation** – a layer of fat under the skin reduces heat loss
- **Buoyancy** – lipids are less dense than water so help animals to float

## CARBOHYDRATES AND LIPIDS IN ENERGY STORAGE

Both lipids and carbohydrates have advantages as energy storage compounds in living organisms. Carbohydrates are usually used for energy storage over short periods and lipids for long-term storage.

**Advantages of lipids**

1. Lipids contain more energy per gram than carbohydrates so stores of lipid are lighter than stores of carbohydrate that contain the same amount of energy

2. Lipids are insoluble in water, so they do not cause problems with osmosis in cells

**Advantages of carbohydrates**

1. Carbohydrates are more easily digested than lipids so the energy stored by them can be released more rapidly

2. Carbohydrates are soluble in water so are easier to transport to and from the store

# Introducing DNA

## THE NUCLEOTIDE SUBUNITS OF DNA

Although DNA is the genetic material of living organisms and is therefore of immense importance, it is made of relatively simple subunits. These are called **nucleotides**. Each nucleotide consists of three parts – a sugar (called deoxyribose), a phosphate group and a base. In diagrams of DNA structure these are usually shown as pentagons, circles and rectangles, respectively. The figure (below) shows how the sugar, the phosphate and the base are linked up in a nucleotide.
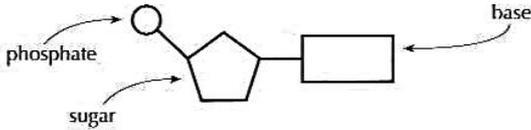
DNA nucleotides do not all have the same base. Four different bases are found – adenine, cytosine, guanine and thymine. These are usually simply referred to as A, C, G and T.

## BUILDING DNA MOLECULES

Two DNA nucleotides can be linked together by a covalent bond between the sugar of one nucleotide and the phosphate group of the other. More nucleotides can be added in a similar way to form a strand of nucleotides.

DNA molecules consist of two strands of nucleotides wound together into a double helix. Hydrogen bonds link the two strands together. These form between the bases of the two strands. However, adenine only forms hydrogen bonds with thymine and cytosine only forms hydrogen bonds with guanine. This is called **complementary base pairing**.
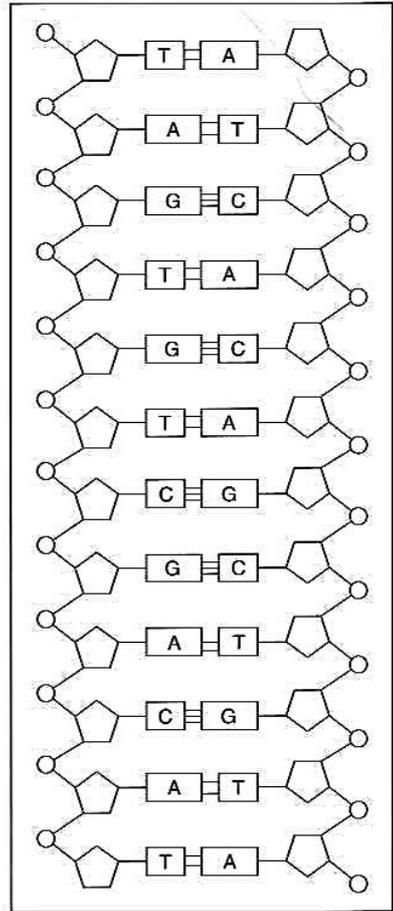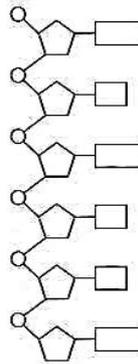
## DNA REPLICATION

DNA replication is a way of copying DNA to produce new molecules with the same base sequence. It is **semi-conservative** – each molecule formed by replication consists of one new strand and one old strand conserved from the parent DNA molecule.

**Stage 1**
The DNA double helix is unwound and separated into strands by breaking the hydrogen bonds. Helicase is the main enzyme involved.
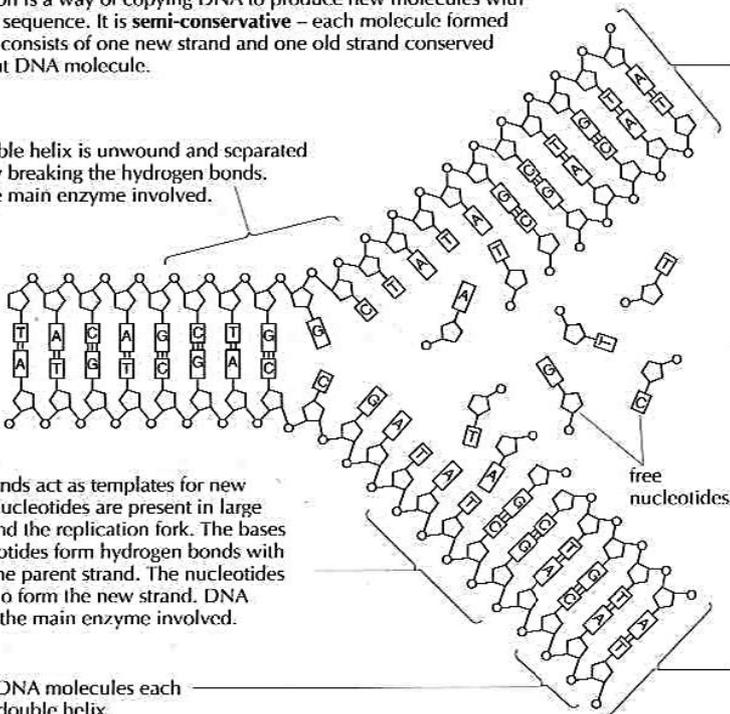
**Stage 2**
The single strands act as templates for new strands. Free nucleotides are present in large numbers around the replication fork. The bases of these nucleotides form hydrogen bonds with the bases on the parent strand. The nucleotides are linked up to form the new strand. DNA polymerase is the main enzyme involved.

**Stage 3**
The daughter DNA molecules each rewind into a double helix.

free nucleotides

The two daughter DNA molecules are identical in base sequence to each other and to the parent molecule, because of complementary base pairing (A pairs with T and C with G). Each of the new strands is **complementary** to the template on which it was made and **identical** to the other template.

16 The chemistry of life

# Transcription and translation

## GENES AND POLYPEPTIDES

Polypeptides are long chains of amino acids. There are twenty different amino acids that can form part of a polypeptide. To make one particular polypeptide, amino acids must be linked up in a precise sequence. Genes store the information needed for making polypeptides. The information is stored in a coded form. The sequence of bases in a gene codes for the sequence of amino acids in a polypeptide.

The information in the gene is decoded during the making of the polypeptide. There are two stages in this process: **transcription** and **translation**.

## DIFFERENCES BETWEEN DNA AND RNA

DNA and RNA both consist of chains of nucleotides, each composed of a sugar, a base and a phosphate. There are three differences between them.

| Feature | DNA | RNA |
|---|---|---|
| Number of strands in the molecule | Two strands forming a double helix | One strand only |
| Type of sugar in each nucleotide | Deoxyribose | Ribose |
| Types of bases contained | A, C, G and T | A, C, G and U Uracil replaces thymine |

## TRANSCRIPTION

Instead of the DNA of genes being used directly to direct the synthesis of polypeptides, a copy is made. The copy is RNA. It carries the information needed to make a polypeptide out into the cytoplasm, so is called mRNA (messenger RNA). The copying of the base sequence of a gene by making an RNA molecule is called **transcription**. In transcription, the same rules of complementary base pairing are followed as in replication, except that uracil pairs with adenine, as RNA does not contain thymine. The RNA molecule produced therefore has a base sequence that is complementary to the transcribed strand and identical to the other DNA strand except that U replaces T.

1. The DNA double helix uncoils and the two strands separate.

Transcription moves along in this direction.

2. Free RNA nucleotides are assembled using **one** of the two DNA strands as the template (the transcribed strand).

3. The RNA nucleotides are linked up to form a strand of RNA.

4. The mRNA separates from the DNA.

5. The DNA double helix reforms.
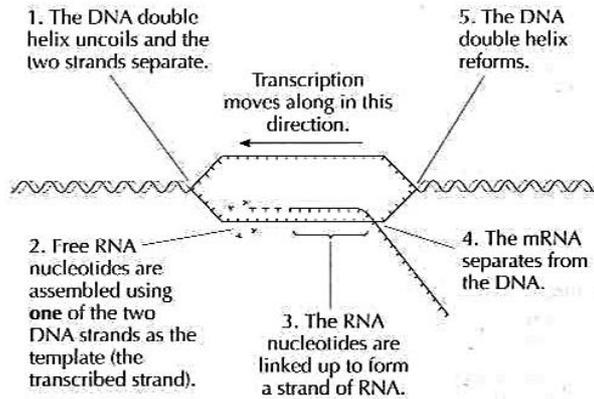
Stages 1, 2 and 3 are all carried out by the enzyme RNA polymerase.

## TRANSLATION

Translation is carried out by ribosomes, using mRNA and tRNA. It is the **genetic code** that is being translated. The genetic code is a triplet code – three bases code for one amino acid. A group of three bases is called a **codon**.

1. Messenger RNA binds to the small subunit of the ribosome. The mRNA contains a series of **codons**, each of which codes for one amino acid.

2. Transfer RNA molecules are present around the ribosome in large numbers. Each tRNA has a special triplet of bases called an **anticodon** and carries the amino acid corresponding to this anticodon.

anticodon

large subunit of ribosome

amino acid

small subunit of ribosome

mRNA

direction of movement of ribosome

3. tRNA molecules bind to the ribosome. Two can bind at once. tRNA can only bind if it has the anticodon that is complementary to the codon on the mRNA. The bases on the codon and anticodon link together by forming hydrogen bonds, following the same rules of complementary base pairing as in replication and transcription.

4. The two amino acids carried by the tRNA molecules are bonded together by a peptide linkage. A dipeptide is formed, attached to the tRNA on the right. The tRNA on the left detaches. The ribosome moves along the mRNA to the next codon. Another tRNA carrying an amino acid binds. A chain of three amino acids is formed. These stages are repeated until a polypeptide is formed.

# Genes, polypeptides and enzymes

## ONE GENE–ONE POLYPEPTIDE HYPOTHESIS

Genes determine the amino acid sequence of proteins. However, some proteins contain more than one type of polypeptide. Hemoglobin is an example of this – it contains two different types of polypeptide. It was found that a different gene is needed to make each polypeptide. Further research has shown that there is almost always a single gene to code for a polypeptide, which does not code for any other polypeptide. This discovery led to an important hypothesis in molecular biology – the one gene–one polypeptide hypothesis. There are some exceptions to this general rule:

- Some genes code for transfer RNA or messenger RNA, not for polypeptides.
- Some DNA sequences act as regulators of gene expression and are not translated into polypeptides.
- In lymphocytes, pieces of DNA from different parts of the genome are spliced together and transcribed and translated to produce antibodies. Different lymphocytes produce different antibodies by splicing together DNA inherited from parents, in different ways.

## INTRODUCING ENZYMES

Catalysts speed up chemical reactions without being changed themselves. Living organisms make biological catalysts called **enzymes**.

*Enzymes are globular proteins which act as catalysts of chemical reactions.*

Without enzymes to catalyse them, many chemical processes happen at a very slow rate in living organisms. By making some enzymes and not others, cells can control what chemical reactions happen in their cytoplasm.

The structure of enzymes is quite delicate and can be damaged by various substances and conditions. This is called **denaturation**.

*Denaturation is changing the structure of an enzyme (or other protein) so that it can no longer carry out its function.*

Denaturation is usually permanent.

In chemical reactions, one or more reactants are converted into one or more products. In reactions catalysed by enzymes, the reactants are called **substrates**.

## ENZYME–SUBSTRATE SPECIFICITY

Most enzymes are specific – they catalyse very few different reactions. They therefore only have a very small number of possible substrates. This is called enzyme–substrate specificity. The substrates bind to a special region on the surface of the enzyme called the **active site**. *An active site is a region on the surface of an enzyme to which substrates bind and which catalyses a chemical reaction involving the substrates.*

The active site of an enzyme has a very intricate and precise shape. It also has distinctive chemical properties. Active sites match the shape and chemical properties of their substrates. Molecules of substrate fit the active site and are chemically attracted to it (right). Other molecules either do not fit or are not chemically attracted. They do not therefore bind to the active site. This is how enzymes are substrate-specific. The way in which the enzyme and substrate fit together is similar to the way in which a key fits a lock. The enzyme is like the lock and the substrate is like the key that fits it.

## Stages in enzyme catalysis
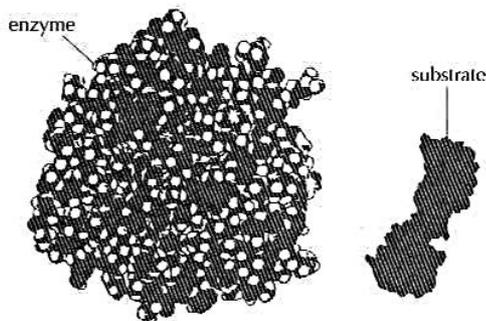


Substrate molecules are in continual random motion. If one collides with the active site it can bind to it.
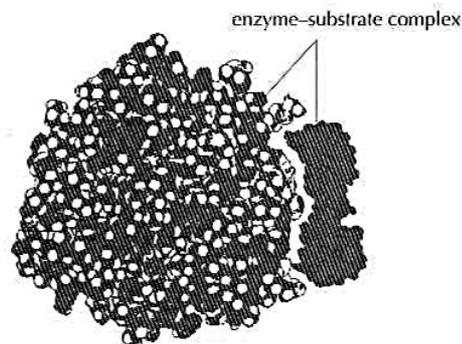


The substrate fits the active site. If other molecules collide with the active site they do not fit and fail to bind.
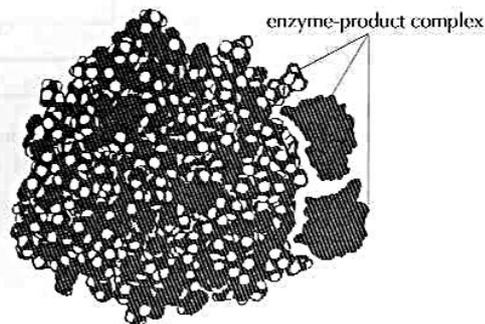


The active site catalyses a chemical reaction. The substrates are turned into products.
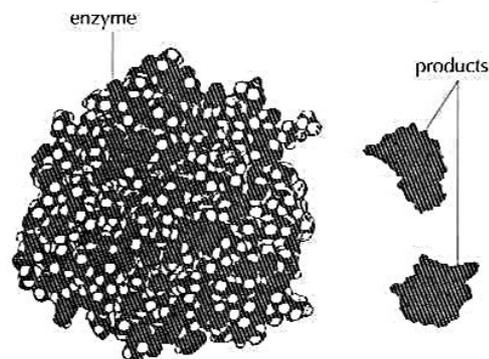


The products detach from the active site, leaving it free for more substrate to bind.

# Enzymes in action

## FACTORS AFFECTING ENZYME ACTIVITY

Wherever enzymes are used, it is important that they have the conditions that they need to work effectively. Temperature, pH and substrate concentration all affect the rate at which enzymes catalyse chemical reactions. The figures (below and right) show the relationships between enzyme activity and substrate concentration, temperature and pH.

## EFFECT OF TEMPERATURE

Enzyme activity increases as temperature increases, often doubling with every 10 °C rise. This is because collisions between substrate and active site happen more frequently at higher temperatures due to faster molecular motion.
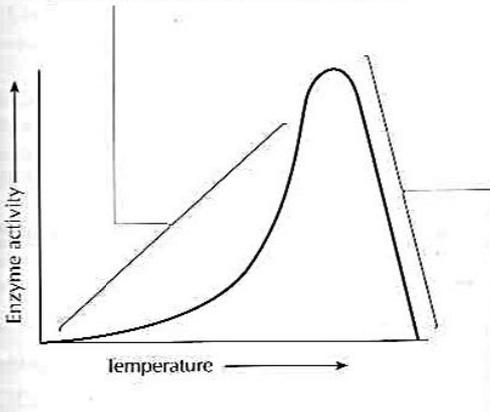
At high temperatures enzymes are denatured and stop working. This is because heat causes vibrations inside enzymes which break bonds needed to maintain the structure of the enzyme.

## EFFECT OF pH

Optimum pH at which enzyme activity is fastest (pH 7 is optimum for most enzymes).

As pH increases or decreases from the optimum, enzyme activity is reduced. Both acids and alkalis can denature enzymes.

## EFFECT OF SUBSTRATE CONCENTRATION

At low substrate concentrations, enzyme activity increases steeply as substrate concentration increases. This is because random collisions between substrate and active site happen more frequently with higher substrate concentrations.
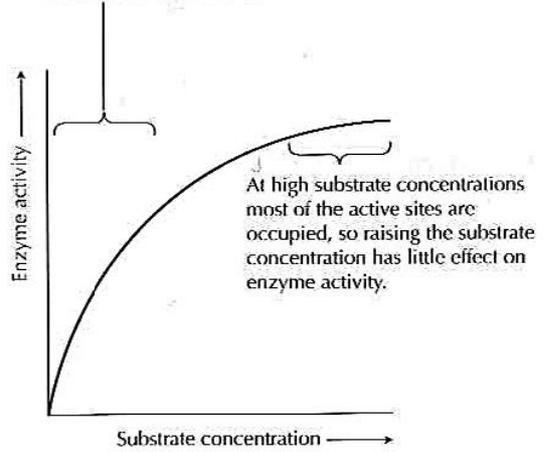
At high substrate concentrations most of the active sites are occupied, so raising the substrate concentration has little effect on enzyme activity.

## LACTASE AND LACTOSE-FREE MILK

Lactose is the sugar that is naturally present in milk. It can be converted into glucose and galactose by the enzyme lactase.

$$lactose \xrightarrow{lactase} glucose + galactose$$

Lactase is obtained from *Kluveromyces lactis*, a type of yeast that grows naturally in milk. Biotechnology companies culture the yeast, extract the lactase from the yeast and purify it, for sale to food manufacturing companies. There are several reasons for using lactase in food processing:

- Some people are lactose intolerant and cannot drink more than about 250 ml of milk per day unless it is lactose-reduced.

- Galactose and glucose are sweeter than lactose, so less sugar needs to be added to sweet foods containing milk, such as milk shakes or fruit yoghurt.

- Lactose tends to crystallize during production of ice cream, giving a gritty texture. Because glucose and galactose are more soluble than lactose they remain dissolved, giving a smoother texture.

- Bacteria ferment glucose and galactose more quickly than lactose, so the production of yoghurt and cottage cheese is faster.

Lactase is used in two ways during food processing:

1. It can be added to milk. The final product contains the enzyme.

2. It can be immobilized on a surface or in beads of a porous material. The milk is then allowed to flow past the immobilised lactase. This avoids contamination of the product with lactase.
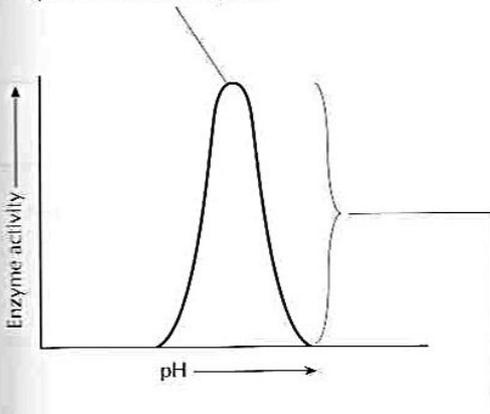
# Cell respiration and energy

## ENERGY AND CELLS

All living cells need a continual supply of energy. This energy is used for a wide range of processes including active transport and protein synthesis. Most of these processes require energy in the form of ATP (adenosine triphosphate). ATP is a chemical substance that can diffuse to any part of the cell and release energy.

Every cell produces its own ATP, by a process called **cell respiration**. In cell respiration, organic compounds such as glucose or fat are carefully broken down. Energy from them is used to make ATP. Cell respiration is defined as *controlled release of energy, in the form of ATP, from organic compounds in cells.*

Cell respiration can be aerobic or anaerobic. Aerobic cell respiration involves the use of oxygen and anaerobic cell respiration does not.

## THE USE OF GLUCOSE IN RESPIRATION

Glucose is often the organic compound that is used in cell respiration. Chemical reactions in the cytoplasm break down glucose into a simpler organic compound called pyruvate. In these reactions a small amount of ATP is made using energy released from glucose.

Glucose ⟶ Pyruvate
⟶ Small amount of ATP
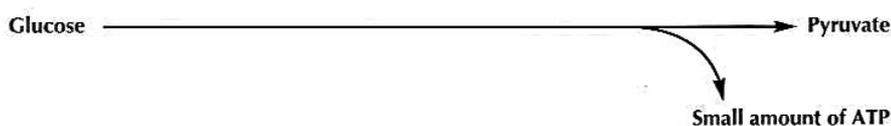
## ANAEROBIC CELL RESPIRATION

If no oxygen is available, the pyruvate remains in the cytoplasm and is converted into a waste product that can be removed from the cell. No ATP is produced in these reactions. In humans the waste product is lactate (lactic acid). In yeast the products are ethanol and carbon dioxide.

Pyruvate ⟶ Humans ⟶ Lactate

Pyruvate ⟶ Yeast ⟶ Ethanol / Carbon dioxide
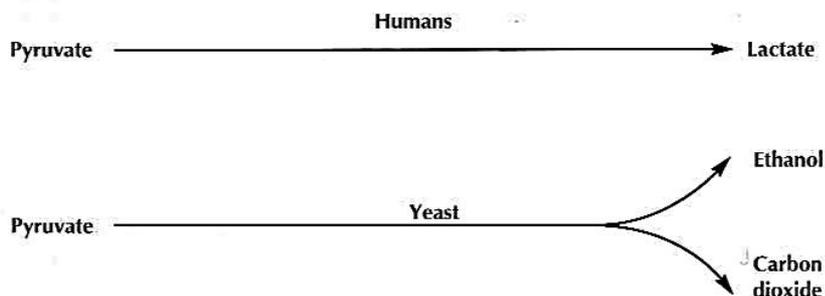
## AEROBIC CELL RESPIRATION

If oxygen is available, the pyruvate is absorbed by the mitochondrion. Inside the mitochondrion the pyruvate is broken down into carbon dioxide and water. A large amount of ATP is produced as a result of these reactions. Aerobic cell respiration therefore has a much higher yield of ATP per gram of glucose than anaerobic cell respiration.

Pyruvate ⟶ Carbon dioxide / Water
⟶ Large amount of ATP
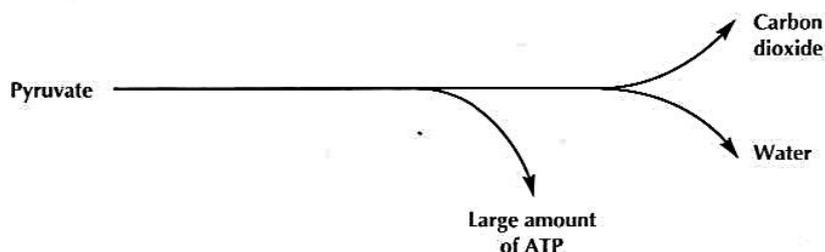
# Photosynthesis

## INTRODUCING PHOTOSYNTHESIS

Photosynthesis is the process used by plants and some other organisms to produce all their own organic substances (food), using only light energy and simple inorganic substances. It involves many stages and some complex chemical reactions, but it can be outlined in a series of statements.

- Photosynthesis involves an energy conversion. Light energy, usually sunlight, is converted into chemical energy.
- Sunlight is called white light, but it is actually made up of a wide range of wavelengths, including red, green and blue.
- Some substances called pigments can absorb light. The main pigment used to absorb light in photosynthesis is chlorophyll.
- The structure of chlorophyll allows it to absorb some colours or wavelengths of light better than others. Red and blue light are absorbed more than green.
- The green light that chlorophyll cannot absorb is reflected. This makes chlorophyll and therefore chloroplasts and plant leaves look green.
- Some of the energy absorbed by chlorophyll is used to produce ATP.
- Some of the energy absorbed by chlorophyll is used to split water molecules. This is called photolysis of water.
- Photolysis of water results in the formation of oxygen and hydrogen. The oxygen is released as a waste product.
- Carbon dioxide is absorbed for use in photosynthesis. The carbon from it is used to make a wide range of organic substances. The conversion of carbon in a gas to carbon in solid compounds is called carbon fixation.
- Carbon fixation involves the use of hydrogen from photolysis and energy from ATP.

## MEASURING RATES OF PHOTOSYNTHESIS

Photosynthesis involves the production of oxygen, the uptake of carbon dioxide and an increase in biomass. Any of these can be used as a measure of the rate of photosynthesis.

### Production of oxygen
Aquatic plants (e.g. *Myriophyllum*) release bubbles of oxygen when they carry out photosynthesis. If these bubbles are collected, their volume can be measured.

### Uptake of carbon dioxide
Leaves take in $CO_2$ from the air or water around them, but this is difficult to measure directly. If $CO_2$ is absorbed from water, the pH of the water rises. This can be monitored with pH indicators or with pH meters.

### Increases in biomass
If batches of plants are harvested at a series of times and the biomass of the batches is determined, the rate of increase in biomass gives an indirect measure of the rate of photosynthesis in the plants.

### Effect of light intensity on photosynthesis



At high light intensities the rate reaches a plateau.

At low to medium light intensities the rate is directly proportional to light intensity.
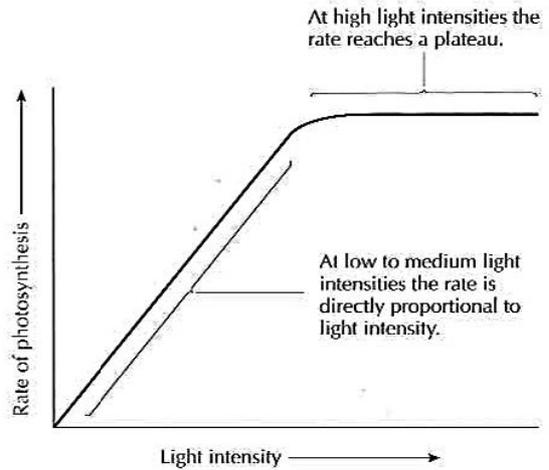
### Effect of $CO_2$ concentration on photosynthesis



At very high $CO_2$ concentrations the rate reaches a plateau.

No photosynthesis at very low $CO_2$ concentrations.

At low to fairly high $CO_2$ concentrations the rate is positively correlated with $CO_2$ concentration.
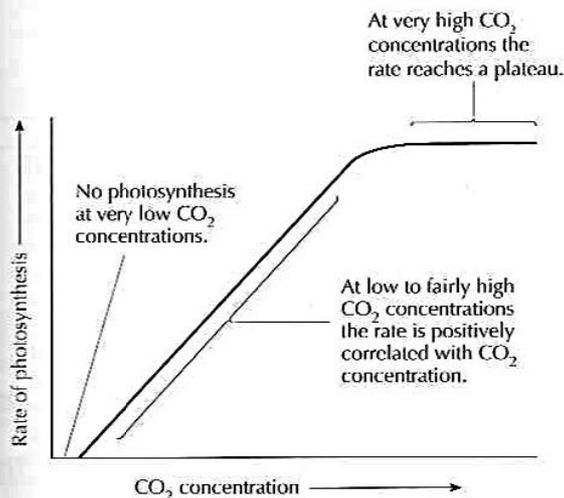
### Effect of temperature on photosynthesis



As temperature increases the rate increases more and more steeply.

Optimum temperature

Above the optimum temperature the rate falls steeply.
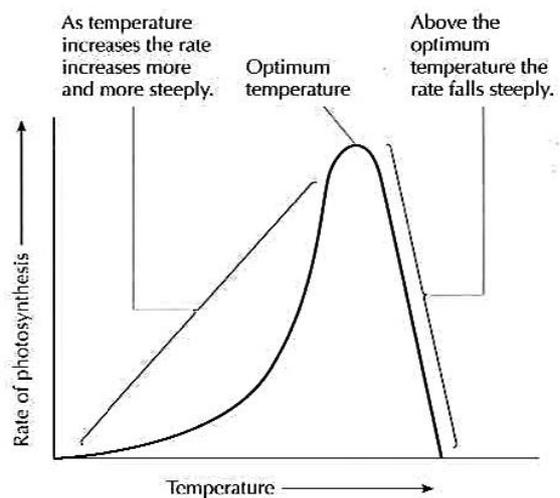
1 The table below shows the base composition of genetic material from ten sources.

| Source of genetic material | Base composition (%) | | | | |
|---|---|---|---|---|---|
| | Adenine | Guanine | Thymine | Cytosine | Uracil |
| Cattle thymus gland | 28.2 | 21.5 | 27.8 | 22.5 | 0.0 |
| Cattle spleen | 27.9 | 22.7 | 27.3 | 22.1 | 0.0 |
| Cattle sperm | 28.7 | 22.2 | 27.2 | 22.0 | 0.0 |
| Pig thymus gland | 30.0 | 20.4 | 28.9 | 20.7 | 0.0 |
| Salmon | 29.7 | 20.8 | 29.1 | 20.4 | 0.0 |
| Wheat | 27.3 | 22.7 | 27.1 | 22.8 | 0.0 |
| Yeast | 31.3 | 18.7 | 32.9 | 17.1 | 0.0 |
| E. coli (bacteria) | 26.0 | 24.9 | 23.9 | 25.2 | 0.0 |
| human sperm | 31.0 | 19.1 | 31.5 | 18.4 | 0.0 |
| influenza virus | 23.0 | 20.0 | 0.0 | 24.5 | 32.5 |

a) Deduce the type of genetic material used by

    (i) cattle [1]

    (ii) E. coli [1]

    (iii) influenza viruses. [1]

b) Suggest a reason for the difference between cattle thymus gland, spleen and sperm in the measurements of their base composition. [1]

c) (i) Explain the reasons for the total amount of adenine plus guanine being close to 50% in the genetic material of many of the species in the table. [3]

    (ii) Identify two other trends in the base composition of the species that have 50% adenine and guanine. [2]

d) (i) Identify a species shown in the table that does not follow the trends in base composition described in (c). [1]

    (ii) Explain the reasons for the base composition of this species being different. [2]

2 The graph (right) shows the results of a data logging experiment. Chlorella, a type of alga that is often used in photosynthesis experiments, was cultured in water in a large glass vessel. Light intensity, temperature and the pH of the water were monitored over a three-day period. The changes in pH were due to changes in carbon dioxide concentration. An increase in $CO_2$ concentration causes a decrease in pH.

a) State the relationship shown in the graph between

    (i) light intensity and $CO_2$ concentration [1]

    (ii) temperature and $CO_2$ concentration. [1]

b) Deduce, from the data in the graph, whether the effect of light intensity or temperature on carbon dioxide concentration is greater. [2]

c) The graph shows both rises and falls in $CO_2$ concentration. Explain the causes of

    (i) rises in $CO_2$ concentration [2]

    (ii) falls in $CO_2$ concentration. [2]
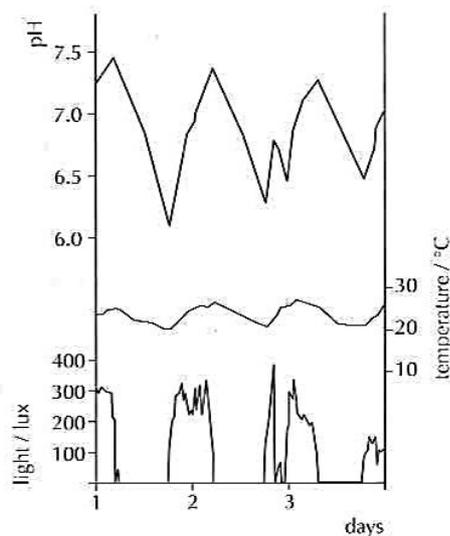
3 The diagram shows the basic structure of amino acids

$$R - \underset{\underset{NH_2}{|}}{\overset{\overset{COOH}{|}}{C}} - H$$
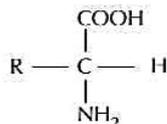
a) State what is represented in the diagram by the letter R. [1]

b) Draw a simple diagram to show how two amino acids are linked together. [2]

c) Amino acids are linked together to form polypeptides at special sites in the cytoplasm of both prokaryotic and eukaryotic cells. Compare the sites where polypeptides are formed in prokaryotic cells with the sites in eukaryotic cells. [2]

# Genes and chromosomes

## GENES

Genetics is the study of variation and inheritance. The basic unit of inheritance is the **gene**. *A gene is a heritable factor that controls a specific characteristic.*

A typical animal or plant cell nucleus contains thousands of genes. The total number of genes in humans is not yet known but is probably between 30 000 and 40 000. All of the genes of an organism are known collectively as the **genome**. *A genome is the whole of the genetic information of an organism.*

## CHROMOSOMES

Genes are made of DNA. They are part of much larger DNA molecules called **chromosomes**. In eukaryotes, proteins are always associated with the DNA in chromosomes.

A typical animal or plant chromosome contains about a 1000 genes, which are arranged in a linear sequence. In any particular type of chromosome the same genes are found arranged in the same sequence. The position of a gene on a chromosome is called the **gene locus**.

## ALLELES

Although one particular chromosome type always has the same genes in the same sequence, the genes themselves can vary. Different forms of many genes can be found. These are called **alleles** of the gene. *An allele is a form of a gene, differing from other alleles of the gene by a few bases at most and occupying the same locus as the other alleles of that gene.*

## REPLICATION OF CHROMOSOMES

If a nucleus is going to divide by mitosis or meiosis, all DNA in the nucleus is replicated. When mitosis or meiosis begins, each chromosome is visible as a double structure (see below). The two parts are called **chromatids** and are connected by a centromere. Some types of chromosome have a **centromere** in the centre and others have a centromere nearer to one end.



8.4kx    20kv 354
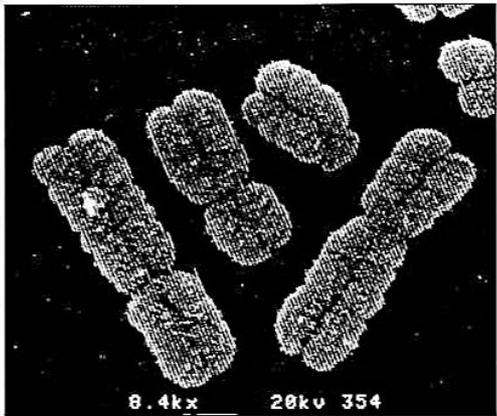
## GENE MUTATION

Genes are almost always passed from parent to offspring without being changed. Occasionally genes do change and this is called **gene mutation**.

*Gene mutation is a change to the base sequence of a gene.* The smallest possible change is when one base in a gene is replaced by another base. This type of gene mutation is called a **base substitution**. Although only one base is changed, the consequences can be very significant. Many gene mutations cause a genetic disease. More than four thousand genetic diseases have been discovered in humans. One example is sickle cell anemia (right).

## Sickle cell anemia – the consequences of a base substitution mutation

Hb is a gene that codes for a polypeptide of 146 amino acids forming part of hemoglobin



Part of Hb$^A$

CTC
GAG

Base substitution from A to T in the triplet coding for the sixth amino acid. The mutation changes Hb$^A$ into a new allele, Hb$^S$

CAC
GTG

Part of Hb$^S$

Transcription

GAG

Transcription

GUG

One codon in the mRNA is different and therefore one amino acid in the poly–peptide is altered

Translation

glutamic acid

CUC
GAG

Translation

valine

CAC
GUG

Effect on the phenotype

Effect on the phenotype

In some conditions red blood cells containing the altered hemoglobin become sickle shaped

Normal red blood cells that carry oxygen efficiently but are affected by malaria

Sickle cells may carry oxygen less efficiently but can give resistance to malaria

The allele Hb$^S$ that causes sickle-cell anemia has become quite common in some parts of the world affected by malaria. In these regions the malaria resistance that it causes is an advantage

# Meiosis

## HAPLOID AND DIPLOID

In most cells the nucleus contains two of each type of chromosome (right). The cell therefore has two full sets of chromosomes. This is called **diploid**. Some cells only contain one of each type of chromosome and therefore have just one set. This is called **haploid**.

In diploid cells each pair of chromosomes have the same genes, arranged in the same sequence. However, they do not usually have the same alleles of all of these genes. They are therefore not identical but instead are **homologous**.

*Homologous chromosomes have the same genes as each other, in the same sequence, but not necessarily the same alleles of those genes.*

The number of chromosomes in a cell can be reduced from diploid to haploid by the process of meiosis. Meiosis is described as a **reduction division**. Living organisms that reproduce sexually have to halve their chromosome number at some stage in the life cycle because the fusion of gametes during fertilization doubles it.

## Chromosomes of a human female



## STAGES OF MEIOSIS



**Prophase I**

Chromosomes pair up. The chromosomes in each pair are homologous

Spindle microtubules grow from each pole to the equator as in mitosis

Nuclear membrane will soon break down

**Metaphase I**

Spindle microtubules from the two poles attach to different chromosomes in each pair, ensuring that one is pulled to one pole and the other to the other pole

**Anaphase I**

The pairs of chromosomes line up on the equator

Homologous chromosomes are pulled to opposite poles. This halves the chromosome number

Each chromosome still consists of two chromatids

The cell membrane around the equator will soon be pulled inwards to divide the cell

**Prophase II**

The cell has divided to form two haploid cells. These immediately divide again – meiosis involves **two divisions**

**Anaphase II**

The centromeres have divided making the chromatids into separate chromosomes which move to opposite poles

New spindle microtubules grow from the poles to the equator

The cell membrane is pulled inwards again to divide the cells

**Telophase II**

Each nucleus now has half as many chromosomes as the nucleus of the parent cell

Nuclear membranes reformed

Both cells have divided again to form four haploid cells

# Karyotypes

## KARYOTYPES AND KARYOTYPING

The number and appearance of the chromosomes in an organism is called the **karyotype**. Living organisms that are members of the same species usually have the same karyotype. The karyotype of a human female is shown on page 24.

From a karyotype, the gender of a person can be deduced and chromosome abnormalities can be detected. The most useful time to do this is before birth. Cells have to be obtained from the fetus. There are two ways of doing this:

### 1. Amniocentesis

A sample of amniotic fluid is removed from the amniotic sac around the fetus. To do this, a hypodermic needle is inserted through the wall of the mother's abdomen and wall of the uterus. Amniotic fluid is drawn out into a syringe. It contains cells from the fetus.

### 2. Chorionic villus sampling

Cells are removed from fetal tissues in the placenta called chorionic villi. As with amniocentesis a hypodermic needle, inserted through the mother's abdomen and uterus wall, is used to obtain the cells.



Once fetal cells have been obtained, they are incubated with chemicals that stimulate them to divide by mitosis. Another chemical is used which stops mitosis in metaphase of mitosis. Chromosomes are most easily visible in metaphase. A fluid is used to burst the cells and spread out the chromosomes. The burst cells are examined using a microscope and a photograph is taken of the chromosomes from one cell (below). The chromosomes in the photograph are cut out and arranged into pairs according to their size and structure. This is called **karyotyping**.
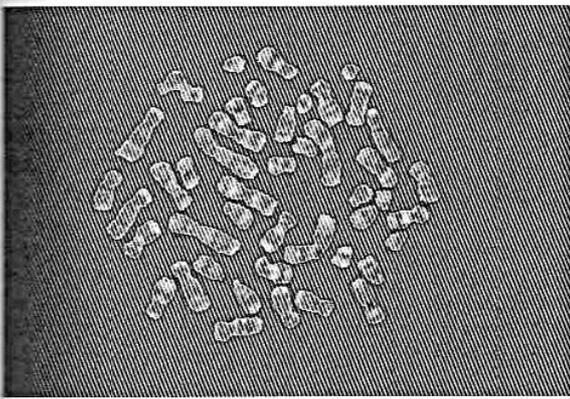


## ANALYSIS OF KARYOTYPES

The gender of the fetus can be determined from the sex chromosomes. Gender determination is described on page 28. Karyotypes can also be analysed to find out whether a fetus has chromosome abnormalities. Sometimes chromosomes that should separate and move to opposite poles during meiosis do not separate and instead move to the same pole. This can happen in either the first (below left) or the second division of meiosis (below right). Non-separation of chromosomes is called **non-disjunction**. The result is that gametes are produced with either one chromosome too many or too few.



Anaphase I          Anaphase II
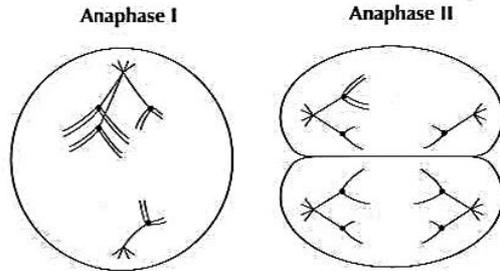
Gametes with one chromosome too few usually quickly die. Gametes with one chromosome too many sometimes survive. When they are fertilised, a zygote is produced with three chromosomes of one type instead of two. For example, in the karyotype (below) there are 47 chromosomes in total with three chromosomes of type 21, rather than two. This causes Down syndrome. It can be due either to non-disjunction during the formation of the sperm or egg. The chance of Down syndrome increases with the age of the parents.
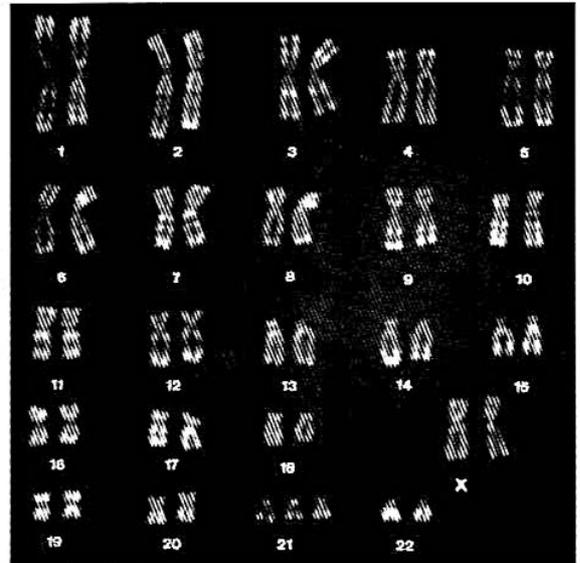
# Monohybrid crosses

## MENDEL'S MONOHYBRID CROSSES

Gregor Mendel is often regarded as the father of genetics. He investigated inheritance by crossing varieties of pea plants that had different characteristics. For example, he crossed a variety that had round seeds with a variety that had wrinkled seeds. He found that all the offspring (called the **F₁ generation**) had the same characteristic as one of the parents. He allowed the F₁ generation to self-fertilize – each plant produced offspring by fertilizing its female gametes with its own male gametes. The offspring (called the **F₂ generation**) contained both of the original parental types. The characteristic that disappeared in the F₁ generation reappeared in a quarter of the F₂ generation. Mendel deduced that inheritance is based on factors that can be passed on from generation to generation. We now call these factors **genes**. Different forms of a gene are called **alleles**. The figure below shows an example of Mendel's monohybrid crosses.

## DEFINITIONS OF TERMS USED IN GENETICS

There are two pairs of terms that are often used by geneticists:
- **Homozygous** – *having two identical alleles of a gene.* All the gametes of a homozygote have the same allele.
- **Heterozygous** – *having two different alleles of a gene.* Half of the gametes of a heterozygote have one of the alleles and half have the other allele.
- **Dominant allele** – *an allele that has the same effect on the phenotype in a heterozygous individual* (where it is combined with a recessive allele) *as in a homozygous individual* (where there are two copies of the dominant allele).
- **Recessive allele** – *an allele that only has an effect on the phenotype in homozygous individuals* (where there are two copies of the recessive allele). In heterozygous individuals the recessive allele is hidden by the dominant allele.

---

### Monohybrid cross between smooth and wrinkled seed pea plants

**P** = parental generation.

**Genotype** = *the alleles possessed by an organism.*

**Phenotype** = *the characteristics of an organism.*

**F₁** = the first filial generation – the offspring of the P generation.

F₁ plants are heterozygous but all have smooth seeds because S is the dominant allele and s is recessive.

The grid shown here is called a **Punnett grid**. It is used to show all the possible outcomes in a cross. In this case both the male and female gametes can be Ⓢ or Ⓢ, giving four possible F₂ genotypes.

P genotype → SS          ss
phenotype → smooth seed    wrinkled seed

gametes → Ⓢ        Ⓢ

F₁ genotype → Ss
phenotype → smooth seed

gametes → Ⓢ Ⓢ

F₂ genotypes and phenotypes:
SS smooth seed
Ss smooth seed
sS smooth seed
ss wrinkled seed

male gametes / female gametes

Seed shape is determined by a single gene. One allele of this gene (S) gives smooth seeds and the other (s) gives wrinkled seeds. The pea plants are diploid so they have two copies of each gene. The parental varieties are both homozygous.

Gametes are produced by meiosis so are haploid and only have one copy of each gene.

When the F₁ hybrid plants produce gametes, the two alleles separate. This is called **segregation**.

Segregation occurs during meiosis. The two alleles of a gene are located on homologous chromosomes which move to opposite poles, causing the segregation (see below).

There is a 3:1 ratio of smooth and wrinkled seed F₂ plants. Crosses between two heterozygous individuals give a 3:1 ratio if one of the alleles is dominant and the other is recessive.

# Inheritance of blood groups

The principles of inheritance discovered by Mendel in pea plants also operate in other plants and in animals. There are, however, sometimes differences and two of these are demonstrated by the inheritance of ABO blood groups in humans – codominance and multiple alleles.

## CROSS INVOLVING CODOMINANT ALLELES

P phenotype ⟶ Group A    X    Group B

genotype ⟶ $I^A I^A$        $I^B I^B$
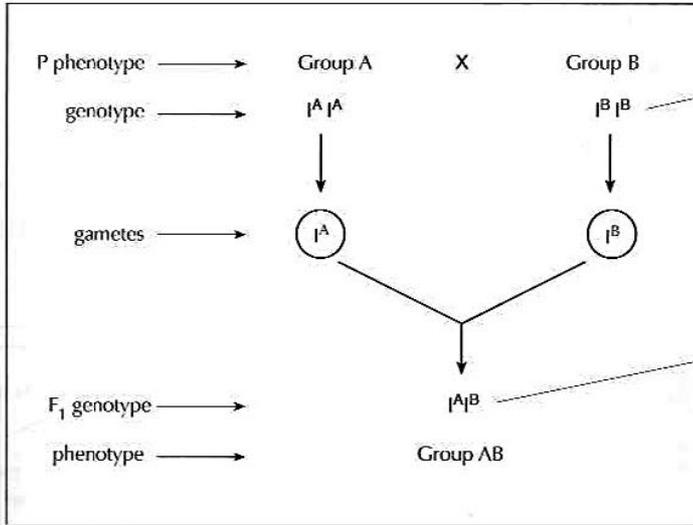
$I^A$ is the allele for blood group A and $I^B$ is the allele for blood group B. Neither allele is recessive, so both are given upper case letters as their symbol.

gametes ⟶ $I^A$      $I^B$

$F_1$ genotype ⟶ $I^A I^B$

phenotype ⟶ Group AB

If $I^A$ and $I^B$ are present together, they both affect the phenotype because they are codominant. Codominant alleles are pairs of alleles that both affect the phenotype when present together in a heterozygote.

## CROSS INVOLVING MULTIPLE ALLELES

P phenotype ⟶ Group A      Group B

genotype ⟶ $I^A i$      $I^B i$
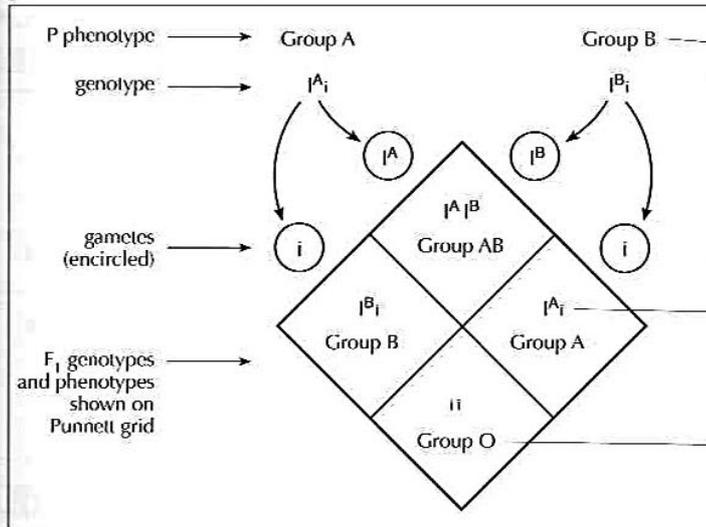
The gene that controls ABO blood groups has a third allele: i. If there are more than two alleles of a gene, they are called *multiple alleles*.

gametes (encircled) ⟶ $I^A$   $I^B$   i   i

$I^A I^B$ Group AB

$I^B i$ Group B

$I^A i$ Group A

i is recessive to both $I^A$ and $I^B$ so $I^A i$ gives blood group A and $I^B i$ gives blood group B.

ii Group O

$F_1$ genotypes and phenotypes shown on Punnett grid

Individuals who are homozygous for i are in blood group O.

## DEDUCING GENOTYPES FROM PEDIGREE CHARTS

A pedigree chart shows the members of a family and how they are related to each other. Males are shown as squares and females as circles. If the phenotypes of the members of the family are known, the genotypes can often be deduced. The figure (right) is a pedigree chart that shows the blood group of each individual. All of the genotypes can be deduced. It is also possible to deduce the probability of the first child of the parents in the third generation being blood group A, B, AB and O.

A × B        AB × AB

O   A × B     O × A   B

A   A × A      A   A
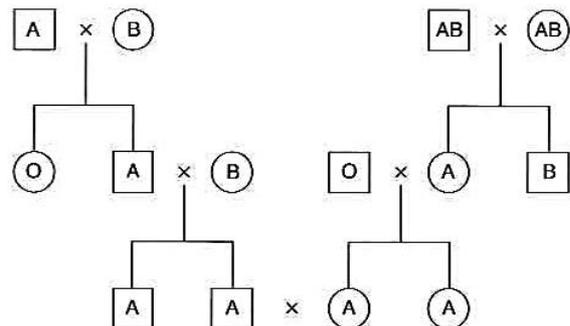
# Genes and gender

## SEX CHROMOSOMES AND GENDER
- Two chromosomes determine the gender of a child (whether it is male or female). These are called the sex chromosomes.
- The X chromosome is relatively large and carries many genes.
- The Y chromosome is much smaller and carries only a few genes.
- If two X chromosomes are present in a human embryo and no Y chromosome, it develops into a girl.
- If one X chromosome and one Y chromosome are present, a human embryo develops into a boy.
- When women reproduce, they pass on one X chromosome in the egg.
- When men reproduce, they pass on either one X or one Y chromosome in the sperm, so the gender of a child depends on whether the sperm that fertilizes the egg is carrying an X or a Y chromosome (right).

**Inheritance of gender in humans**
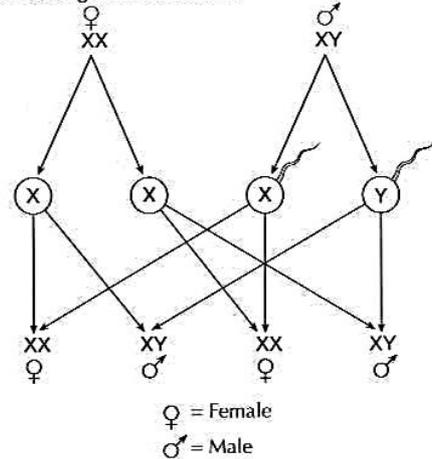


$\female$ = Female
$\male$ = Male

## SEX LINKAGE
If a gene is carried on the X chromosome, the pattern of inheritance is different for males and females – there is sex linkage. *Sex linkage is the association of a characteristic with gender, because the gene controlling the characteristic is located on a sex chromosome.* Sex-linked genes are almost always located on the X chromosome. Females have two X chromosomes and therefore have two copies of sex linked genes. Males only have one X chromosome and therefore only have one copy of sex linked genes. In humans, hemophilia (below) and red–green colour blindness are examples of sex-linked characteristics.

## CHOOSING SYMBOLS FOR ALLELES
These rules are usually followed when choosing symbols for alleles:
1. **One dominant and one recessive allele of a gene**
   A letter is chosen. The dominant allele is shown with the upper case, and the recessive allele with the lower case letter (e.g. A and a)
2. **Co-dominant alleles**
   A letter is chosen. This letter and a superscript letter represent each allele. (e.g. $C^w$ and $C^r$)
3. **Sex-linked dominant and recessive alleles**
   The letter X is used to show the X chromosome. Each allele is shown superscript. (e.g. $X^H$ and $X^h$)

---

**Example of a cross involving sex linkage**

**The diagram below shows how two parents, neither of whom have hemophilia, could have a hemophiliac son.**

The mother is heterozygous but is not a hemophiliac because H is dominant and h is recessive. She is a **carrier** of the allele for hemophilia.

*A carrier has a recessive allele of a gene but it does not affect the phenotype because a dominant allele is also present.*

KEY

$X^H$ X chromosome carrying the allele for normal blood clotting

$X^h$ X chromosome carrying the allele for hemophilia.



The Y chromosome does not carry either allele of the gene.

None of the female offspring are hemophiliac because they all inherited the father's X chromosome which carries the allele for normal blood clotting (H), but there is a 50% chance of a daughter being a carrier.

There is a 50% chance of a son being hemophiliac as half of the eggs produced by the mother carry $X^h$.
The chance of a daughter being hemophiliac is 0%, so the overall chance of offspring being hemophiliac is 25%.

# Deducing genotypes

## USING PEDIGREE CHARTS

Pedigree charts can be used to deduce whether a character is caused by a dominant or recessive allele and whether it is sex-linked or not. They can also be used to deduce the genotypes of individuals. The figures (below) are pedigree charts that each show a different pattern of inheritance. Squares represent males and circles represent females. Shaded symbols represent individuals affected by the condition and unshaded symbols represent unaffected individuals. The probability of the different phenotypes in the offspring of some of the couples in the pedigrees (marked with an asterisk *) can be determined.

## MUSCULAR DYSTROPHY
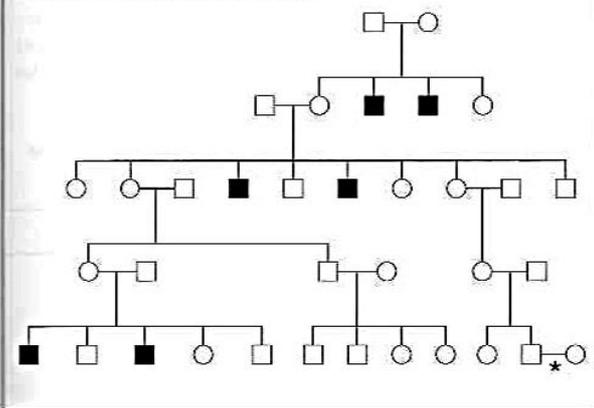


## ALBINISM
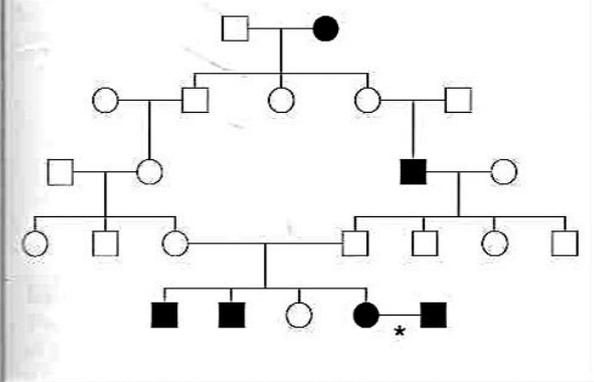


## HUNTINGTON'S DISEASE
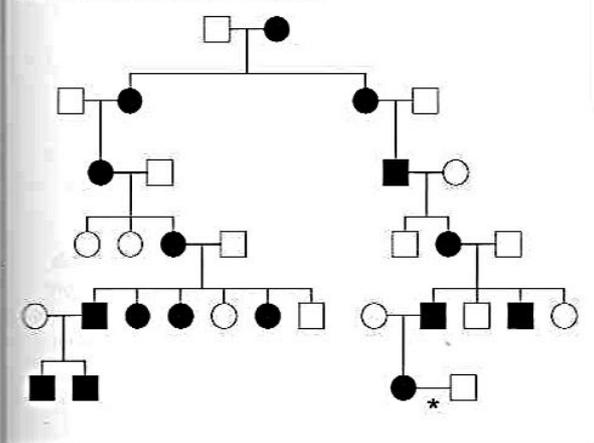


## USING TEST CROSSES

It is not always possible to discover whether an individual has a gene, or does not have it, by looking at the individual's phenotype. If one allele of a gene is dominant and another allele is recessive, an individual with two copies of the dominant allele has the same phenotype as an individual with one dominant and one recessive allele. These two genotypes can be distinguished by carrying out a **test cross**.

*In a test cross an individual that might be heterozygous is crossed with an individual that is homozygous recessive.*

**Example of a test cross**

A farmer is unsure whether his bull is a purebred Hereford or whether it is a Hereford x Aberdeen Angus hybrid. Hereford cattle have a white head caused by a dominant allele (H). Aberdeen Angus cattle have black heads caused by a recessive allele of the same gene (h). The farmer crosses his bull with 100 Aberdeen Angus cows. The figures below show the possible outcomes.



White-headed bull    X    Black-headed cows

WW              ww

(W)           (w)
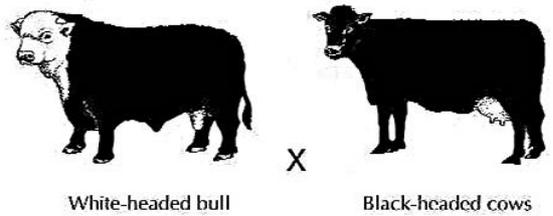
Ww
All offspring have
white heads



White-headed bull    X    Black-headed cows

Ww              ww

(W)    (w)       (w)
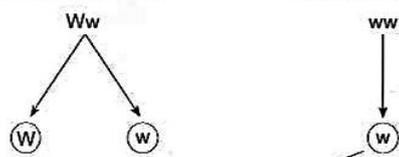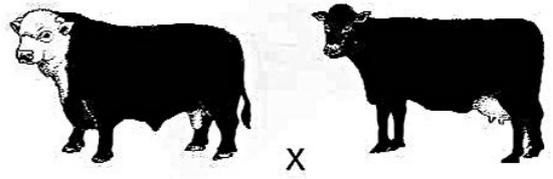
Ww        ww
1:1 ratio of white
and black heads

# DNA profiling

## PCR – POLYMERASE CHAIN REACTION

In the polymerase chain reaction, DNA is copied again and again to produce many copies of the original molecules. Millions of copies of the DNA can be produced in a few hours. This is very useful when very small quantities of DNA are found in a sample and larger amounts are needed for analysis. DNA from very small samples of semen, blood or other tissue or even from long-dead specimens can be amplified using PCR.

PCR is carried out at high temperatures using a DNA polymerase enzyme from *Thermus aquaticus*, a bacterium that lives in hot springs.

## GEL ELECTROPHORESIS

Gel electrophoresis is a method of separating mixtures of proteins, DNA or other molecules that are charged. The mixture is placed on a thin sheet of gel, which acts like a molecular sieve. An electric field is applied to the gel by attaching electrodes to both ends. Depending on whether the particles are positively or negatively charged, they move towards one of the electrodes or the other. The rate of movement depends on the size and charge of the molecules – small and highly charged molecules move faster than larger or less charged ones.

## DNA PROFILING

Humans and other organisms have short sequences of bases that are repeated many times called satellite DNA. This satellite DNA varies greatly between different individuals in the number of repeats. If it is copied using PCR and then cut up into short fragments using restriction enzymes, the lengths of the fragments vary greatly between individuals. Gel electrophoresis can be used to separate fragmented pieces of DNA according to their charge and size. The pattern of bands on the gel is very unlikely to be the same for any two individuals. This technique, called DNA profiling or DNA fingerprinting has many applications, including forensic investigations (obtaining evidence to use in court cases) and investigating paternity (who the father of a child is).

### Forensic use of DNA profiling
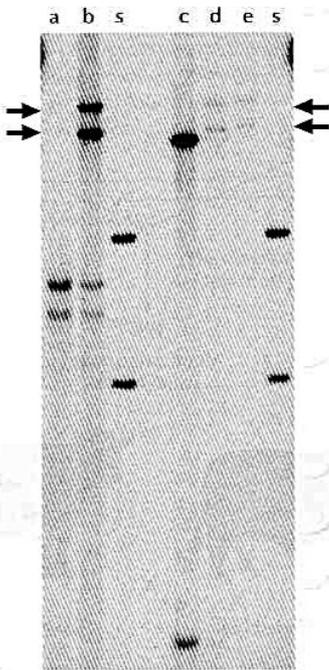


The first use of DNA profiling was in the Enderby double murder case. The DNA profiles show clearly whether the prime suspect was guilty.

- a = hair roots from the first victim
- b = mixed semen and vaginal fluids from the first victim
- c = blood of second victim
- d = vaginal swab from second victim
- e = semen stain on second victim
- s = blood of prime suspect.

The two bands indicated by arrows are from DNA in the culprit's semen.

### Testing paternity using DNA profiling
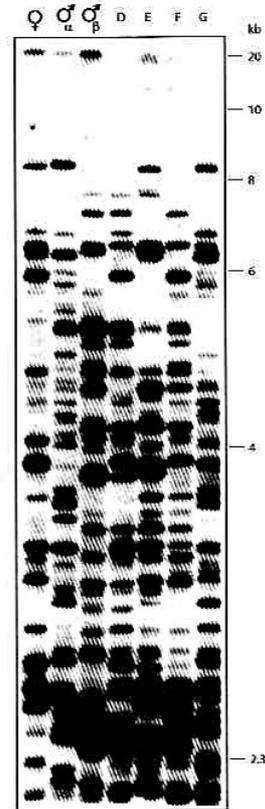


The DNA profiles of a family of dunnocks (*Prunella modularis*) are shown above. Dunnocks are small birds found in Europe, North Africa and Asia. The tracks from left to right are: the female, two resident males that might have been the father of the offspring and four offspring. The results show that the β male fathered three of the four offspring (D, E and F), despite being less dominant than the α male.

# Genetic modification

## GENETIC MODIFICATION AND ITS USES

The genetic code is universal, so genes can be transferred from one organism to another, even if they are members of different species. A gene codes for a polypeptide with the same amino acid sequence, whether it is in a human cell, a bacterium or any other cell. Organisms that have had genes transferred to them are called **genetically modified organisms** (GMO) or transgenic organisms. The process of transferring genes is called genetic modification. One example is the transfer of a gene for factor IX (a blood clotting factor) from humans to sheep, where it is produced in the sheep's milk. Another example is the transfer of the gene for resistance to the herbicide glyphosate from a bacterium to crop plants, so that the crop can be sprayed with the herbicide.

## Techniques used for gene transfer into bacteria



Messenger RNA coding for insulin is extracted from human pancreas cells that make insulin.

DNA copies of the messenger RNA are made using the enzyme reverse transcriptase.

Sticky ends are made by adding extra G nucleotides to the ends of the gene.

The insulin gene and the plasmid are mixed. They link by complementary base pairing (C – G), between the sticky ends.

Plasmids are small loops of DNA found in bacteria.

Plasmids are cut open using restriction enzymes.

Restriction enzymes cut DNA at specific base sequences.

Sticky ends are made by adding extra C nucleotides to the ends of the cut plasmid.

DNA ligase seals up the nicks in the DNA by making sugar–phosphate bonds.

Human insulin

The E.coli bacteria start to make human insulin, which is extracted, purified and used by diabetics.

The genetically modified E.coli are cultured in a fermenter.

The recombinant plasmids are mixed with the host cells. The host cells absorb them.

A suitable host cell is chosen to receive the gene, in this case a strain of E.coli bacteria.

The plasmid with the human insulin gene inserted is called a recombinant plasmid.

## BENEFITS AND RISKS OF GENETIC MODIFICATION

The production of human insulin using bacteria has enormous benefits and no obvious harmful effects. There are other examples of genetic modification that are more controversial. Maize crops are often seriously damaged by corn borer insects. A gene from a bacterium (*Bacillus thuringiensis*) has been transferred to maize. The gene codes for a bacterial protein called Bt toxin that kills corn borers feeding on the maize.

### Potential benefits of Bt maize

1. Less pest damage and therefore higher crop yields to help to reduce food shortages

2. Less land needed for crop production, so some could become areas for wildlife conservation

3. Less use of insecticide sprays, which are expensive and can be harmful to farm workers and to wildlife

### Possible harmful effects of Bt maize

1. Humans or farm animals that eat the genetically modified maize might be harmed by the bacterial DNA in it, or by the Bt toxin

2. Insects that are not pests could be killed. Maize pollen containing the toxin is blown onto wild plants growing near the maize. Insects feeding on the wild plants, including Monarch butterfly caterpillars, are therefore affected even if they do not feed on the maize

3. Populations of wild plants might be changed. Cross-pollination will spread the Bt gene into some wild plants but not others. These plants would then produce the Bt toxin and have an advantage over other wild plants in the struggle for survival

# Cloning

## CLONES AND CLONING

Cloning is producing identical copies of genes, cells or organisms. The products of cloning are called a **clone**.
*A clone is a group of genetically identical organisms or a group of genetically identical cells derived from a single parent cell.*
Cloning is very useful if an organism has a desirable combination of characteristics and more organisms with the same characteristics are wanted – this is reproductive cloning. Sometimes cloning is used to produce skin or other tissues needed to treat a patient – this is therapeutic cloning.

## PLANT AND ANIMAL CLONING

Most plants can be cloned quite easily from pieces of root, stem or leaf. Animals cannot be cloned in the same way from parts of their bodies. If animal embryos are divided up at an early stage into several pieces, each piece can develop into a separate animal. (This happens naturally when identical twins are formed.) However, it is hard to predict which embryos will develop into animals with desirable characteristics and should therefore be cloned. The first successful reproductive cloning of an adult with known characteristics produced Dolly the sheep (below).

## Techniques for cloning using differentiated cells



The egg cells without nuclei were fused with the donor cells using a pulse of electricity.

The fused cells developed like zygotes and became embryos.

Udder cells were taken from a donor sheep. The cells were cultured in a low nutrient medium to make them switch off their genes and become dormant.

The nucleus was removed from each egg cell using a micropipette.

One lamb was born successfully and was named Dolly. Dolly is genetically identical to the sheep whose udder cells were used.

Unfertilized egg cells were taken from another sheep.

The embryos were implanted into another sheep who became the surrogate mother.

## THERAPEUTIC CLONING IN HUMANS

Techniques are being developed to create human embryos, from which embryonic stem cells can be obtained for medical use. These stem cells have the capacity to divide and differentiate into any types of human cell. They could be used to replace tissues or even organs that have become damaged or lost in a patient. There are many ethical issues involved and research into therapeutic cloning has been banned in some countries.

### Arguments for therapeutic cloning

1. Embryonic stem cells can be used for therapies that save lives and reduce suffering.

2. Cells can be removed from embryos that have stopped developing, so would have died anyway.

3. Cells are removed at a stage when embryos have no nerve cells and cannot feel pain.

### Arguments against therapeutic cloning

1. Every human embryo is a potential human being, which should be given a chance of developing.

2. More embryos may be produced than are needed, so some may have to be killed.

3. There is a danger of embryonic stem cells developing into tumour cells.

## THE HUMAN GENOME PROJECT

The human genome has been estimated to consist of between 25 000 and 30 000 genes. The Human Genome Project aims to find the location of all of these genes on the human chromosomes and the base sequence of all of the DNA that makes them up. The project is an international cooperative one, with laboratories in many countries involved.

The sequencing of the entire human genome will make it easier to study how genes influence human development. It will allow easier identification of genetic diseases. It will allow the production of new drugs based on DNA base sequences of genes or the structure of proteins coded for by these genes. It will give us new insights into the origins, evolution and migrations of humans.

# EXAM QUESTIONS ON TOPIC 4

1  In humans the blood groups A, B, AB and O are determined by three alleles of an autosomal gene: $I^A$, $I^B$ and i. Alleles $I^A$ and $I^B$ are codominant and allele i is recessive. The phenotypes of some individuals in the pedigree below are shown.
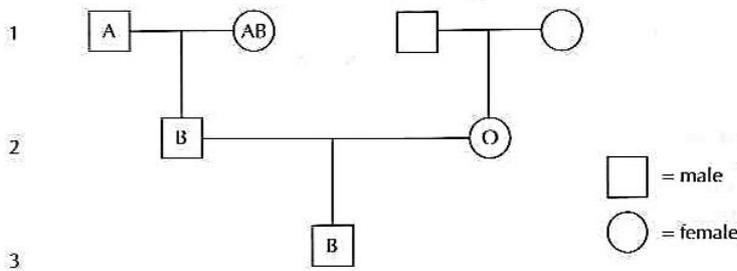


    a) Explain the conclusions that can be drawn about the genotypes of the individuals in the pedigree in generations 2 and 3.                                                                                    [3]

    b) Explain to which blood groups the parents of the blood group O female in the pedigree could have belonged.                                                                                          [3]

    c) Suggest one reason for testing the blood groups in humans.                                      [1]

2  When red and white flowered *Mirabilis jalapa* plants are crossed together, all the offspring have pink flowers. The symbols for the two alleles involved are $C^r$ (red) and $C^w$ (white).

    a) State the genotypes of the red- and white-flowered parents and the pink-flowered offspring.     [1]

    b) When Mendel crossed red- and white-flowered pea plants together, all of the offspring had red flowers. Suggest a reason for the difference in results between pea plants and *Mirabilis jalapa* plants.   [1]

    c) Predict the outcome of a cross between two pink-flowered *Mirabilis jalapa* plants, using a Punnett grid.                                                                                          [3]

3  a) Define clone.                                                                                    [1]

    b) Outline one technique for cloning animals, using differentiated cells.                          [2]

    The DNA profiles of sheep are shown (right).

    U = differentiated cells taken from the udder of a sheep that was used in cloning experiments

    C = cells in a culture derived from the udder cells

    D = blood cells taken from Dolly the sheep

    1–12 = results from 12 other sheep.

    c) (i) Explain whether DNA fragments in the profiles had moved upwards or downwards.               [2]

       (ii) Explain the conclusions that can be drawn from the DNA profiles of the sheep.              [3]
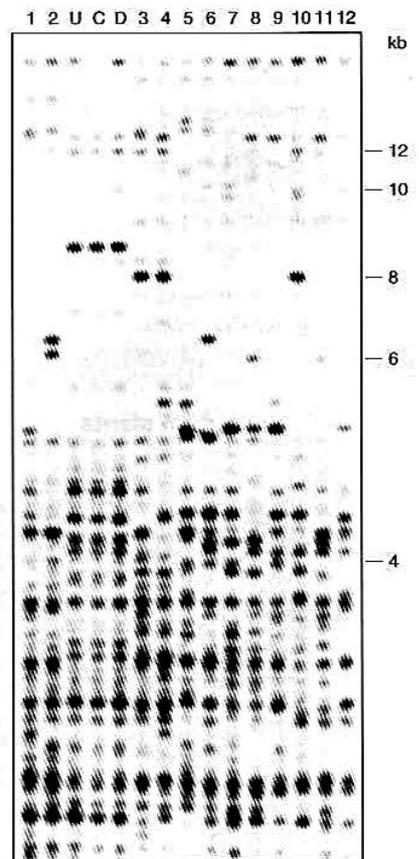
# Identifying living organisms

## USING KEYS TO IDENTIFY ORGANISMS

The first stage in many ecological investigations is to find out what species of organism there are in the area being studied. This is called **species identification**. This can be done using **keys**.

Keys for species identification are usually constructed in this way:
- the key consists of a series of numbered stages
- each stage consists of a pair of alternative characteristics
- some alternatives give the next stage of the key to go to
- some alternatives give the identification.

## Identifying aquarium plants using a key

Many aquatic plants in aquariums in biology laboratories belong to one of these four genera:
- *Cabomba*
- *Ceratophyllum*
- *Elodea*
- *Myriophyllum*

All of these plants have cylindrical stems with whorls of leaves. The shape of four leaves is shown in the figure (left). A key can be used to identify which of the four genera a plant belongs to, if it is known to be in one of them.

1. Simple undivided leaves . . . . . . . . . . . . . . . . . . . . .*Elodea*

   Leaves forked or divided into segments . . . . . . . . . . . . . .2

2. Leaves forked once or twice to form
   two or four segments . . . . . . . . . . . . . . . . .*Ceratophyllum*

   Leaves divided into more than four segments . . . . . . . . .3

3. Leaves divided into many flattened segments . . . .*Cabomba*

   Leaves divided into many
   filamentous segments . . . . . . . . . . . . . . . .*Myriophyllum*

Some species of Elodea have recently been moved by taxonomists to other genera:
Elodea densa is now *Egeria densa*.
Elodea crispa is now *Lagarosiphon major*.

## Leaves of aquarium plants
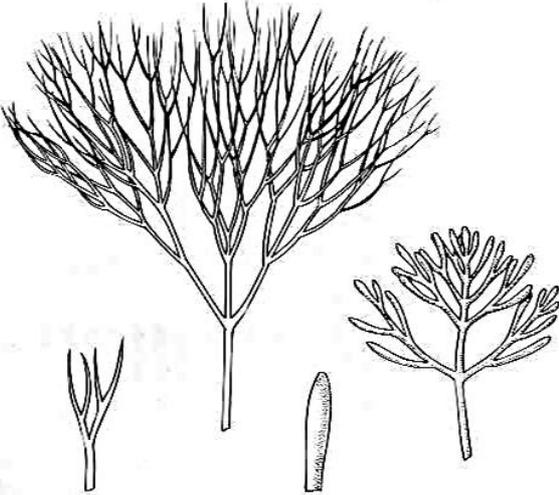
## Constructing a key

The five animals shown below are found in beehives. It would be useful to construct a key to allow a beekeeper to identify them, as some of them are very harmful and others are harmless to honey bees.
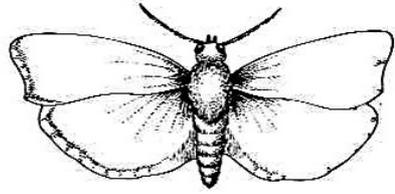
*Galleria mellonella*
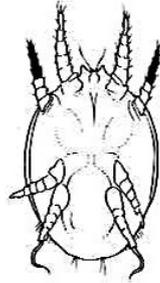
*Acarus siro*
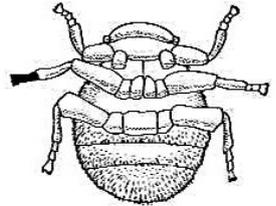
*Braula coeca*
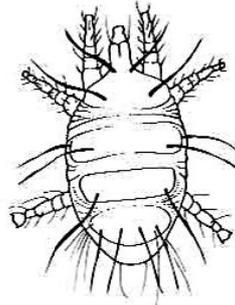
*Acarapis woodi*
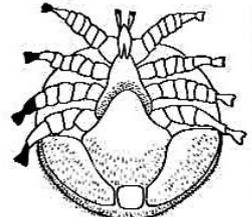
*Varroa jacobsonii*

## BINOMIAL NOMENCLATURE

In the classification of living organisms, the basic group is the **species**.

*A species is a group of organisms with similar characteristics, which can interbreed and produce fertile offspring.*

Every species is classified into a **genus**. A genus is a group of similar species.

Each species needs an international name, so that biologists throughout the world can refer to it. The naming of species is called **nomenclature**. The nomenclature that biologists use is called the **binomial system** because two names are used to refer to each species. The key features of the binomial system of nomenclature are:
- the first name is the genus name
- the genus name is given an upper case first letter
- the second name is the species name
- the species name is given a lower case first letter
- italics are used when the name is printed
- the name is underlined if it is hand-written.

# Classification of plants and animals

## CLASSIFICATION FROM SPECIES TO KINGDOM


*Balaenoptera musculus*

A group of organisms, such as a species or a genus is called a **taxon**. Species are classified into a series of taxa, each of which includes a wider range of species than the previous one. This is called the **hierarchy of taxa**.
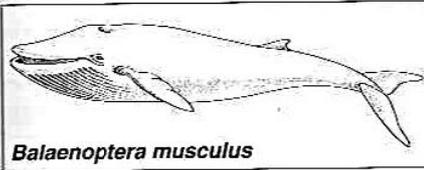
|  | Animal example<br>Balaenoptera musculus<br>– the blue whale (left) | Plant example<br>Sequoia sempervirens<br>– the coast redwood (right) |
|---|---|---|
| Species that are similar are grouped into a genus | Genus Balaenoptera | Genus Sequoia |
| Genera that are similar are grouped into a family | Family Balaenopteridae | Family Taxodiaceae |
| Families that are similar are grouped into an order | Order Cetacea | Order Pinales |
| Orders that are similar are grouped into a class | Class Mammalia | Class Pinopsida |
| Classes that are similar are grouped into a phylum | Phylum Chordata | Phylum Coniferophyta |
| Phyla that are similar are grouped into a kingdom | Kingdom Animalia | Kingdom Plantae |


*Sequoia sempervirens*

## Plant classification

There are four main phyla of plants, which can be easily distinguished by studying their external structure.

| | Roots, leaves and stems | Maximum height | Reproductive structures |
|---|---|---|---|
| **Bryophytes – mosses** | Bryophytes have no roots, only structures similar to root hairs called **rhizoids**. Mosses have simple leaves and stems. Liverworts consist of a flattened thallus | 0.5 metres | Spores are produced in a capsule. The capsule develops at the end of a stalk |
| **Filicinophytes – ferns** | Ferns have roots, leaves and short non-woody stems. The leaves are usually curled up in bud and are often **pinnate** – divided into pairs of leaflets | 15 metres | Spores are produced in sporangia, usually on the underside of the leaves |
| **Coniferophytes – conifers** | Conifers are shrubs or trees with roots, leaves and woody stems. The leaves are often narrow with a thick waxy cuticle | 100 metres | Seeds are produced. The seeds develop from ovules on the surface of the scales of female **cones**. Male cones produce pollen |
| **Angiospermo-phytes – flowering plants** | Flowering plants are very variable but usually have roots, leaves and stems. The stems of flowering plants that develop into shrubs and trees are woody | 100 metres | Seeds are produced. The seeds develop from ovules inside **ovaries**. The ovaries are part of **flowers**. **Fruits** develop from the ovaries, to disperse the seed |

## ANIMAL CLASSIFICATION

There are over thirty phyla of animals. The external recognition features of six of these phyla are shown here.

**Porifera**
- no clear symmetry
- attached to a surface
- pores through body
- no mouth or anus
Examples: *sponges*
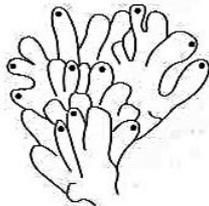


**Cnidaria**
- radially symmetric
- tentacles
- stinging cells
- mouth but no anus
Examples: *jellyfish, corals, sea anemones*
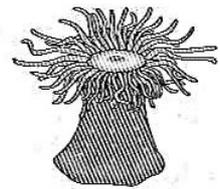


**Platyhelminths**
- bilaterally symmetric
- flat bodies
- unsegmented
- mouth but no anus
Examples: *Planaria, tapeworms, liverflukes*
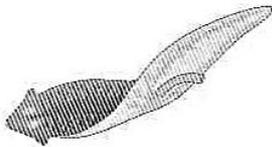


**Annelida**
- bilaterally symmetric
- bristles often present
- segmented
- mouth and anus
Examples: *earthworms, leeches, ragworms*
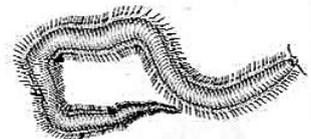


**Mollusca**
- muscular foot and mantle
- shell usually present
- segmentation not visible
- mouth and anus
Examples: *slugs, snails, clams, squids*
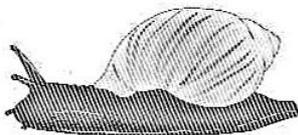


**Arthropoda**
- bilaterally symmetric
- exoskeleton
- segmented
- jointed appendages
Examples: *insects, spiders, crabs, millipedes*
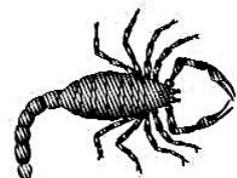
# Population dynamics

## CHANGES TO THE SIZE OF A POPULATION

*A population is a group of organisms of the same species, who live in the same area at the same time.*

There are four ways in which the size of a population can change:

- Offspring are produced and are added to the population – **natality**.
- Individuals die and are lost from the population – **mortality**.
- Individuals move into the area from elsewhere and are added to the population – **immigration**.
- Individuals move out of the area to live elsewhere – **emigration**.

Populations are often affected by all four of these things and the overall change can be calculated using an equation:

$$\text{Population change} = (\text{natality} + \text{immigration}) - (\text{mortality} + \text{emigration})$$

## POPULATION GROWTH CURVES

If the size of a population is measured regularly, a curve can be plotted. When a species spreads into a new area, the population growth curve is often sigmoid (S-shaped). The three phases of this curve are explained by changes in natality and mortality.

### 1. Exponential phase

The population increases exponentially because the natality rate is higher than the mortality rate. The resources needed by the population such as food are abundant, and diseases and predators are rare.

### 2. Transitional phase

The natality rate starts to fall and/or the mortality rate starts to rise. Natality is still higher than mortality so the population still rises, but less and less rapidly.

### 3. Plateau phase

Natality and mortality are equal so the population size is constant. Something has limited the population such as:

- shortage of resources, e.g. food.
- more predators.
- more disease or parasites.

All of these factors limit population increase because they become more intense as the population rises and becomes more crowded. They either reduce the natality rate or increase the mortality rate.

If the population is limited by a shortage of resources, it has reached the **carrying capacity** of the environment. The carrying capacity is the maximum population size that can be supported by the environment.

*Population size* (y-axis)

*Time* (x-axis)

# Evidence for evolution

## EVOLUTION OF POPULATIONS

The word evolution has several meanings, all of which involve the gradual development of things. In biology, the word has come to mean the changes that occur in living organisms, over many generations. Evolution happens in populations of living organisms. It only happens with characteristics that can be inherited.

*Evolution is the cumulative change in the heritable characteristics of a population.* Although it is not possible to prove, using the scientific method, that the organisms on Earth today are the result of evolution, there is much evidence that makes it very likely. Three types of evidence are illustrated on this page.

## HOMOLOGOUS ANATOMICAL STRUCTURES

There are also remarkable similarities between some groups of organisms in their structure. For example, bones in the limbs of vertebrates are strikingly similar, despite being used in many different ways (below). The structure is called the pentadactyl limb.
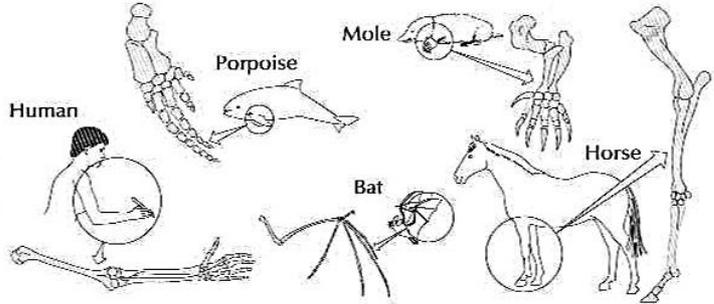


The most likely explanation for these structural similarities is that the organisms have evolved from a common ancestor. Structures that have developed from the same part of a common ancestor are called homologous structures.

## THE FOSSIL RECORD – PALAEONTOLOGY

**Fossil of *Acanthostega***



Eight fingers

Seven toes
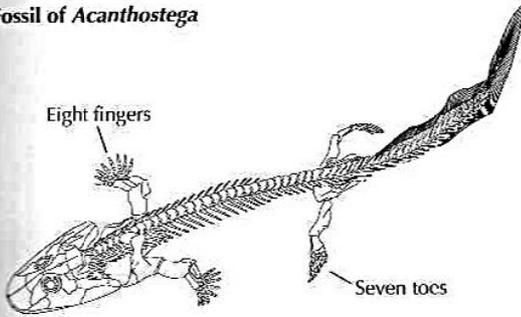
The existence of fossils is very difficult to explain without evolution. An example of this is *Acanthostega*. The figure (left) is a drawing of a 365 million year old fossil of *Acanthostega*. It has similarities to other vertebrates, with a backbone and four limbs, but it has eight fingers and seven toes, so it is not identical to any existing organism. This suggests that vertebrates and other organisms change over time. *Acanthostega* is an example of a "missing link". Although it has four legs, like most amphibians, reptiles and mammals, it also had a fish-like tail and gills and lived in water. This shows that land vertebrates could have evolved from fish via an aquatic animal with legs.

## SELECTIVE BREEDING OF DOMESTICATED ANIMALS

The breeds of animal that are reared for human use are clearly related to wild species and in many cases can still interbreed with them. These domesticated breeds have been developed from wild species, by selecting individuals with desirable traits, and breeding from them. The striking differences in the heritable characteristics of domesticated breeds give us evidence that species can evolve rapidly.
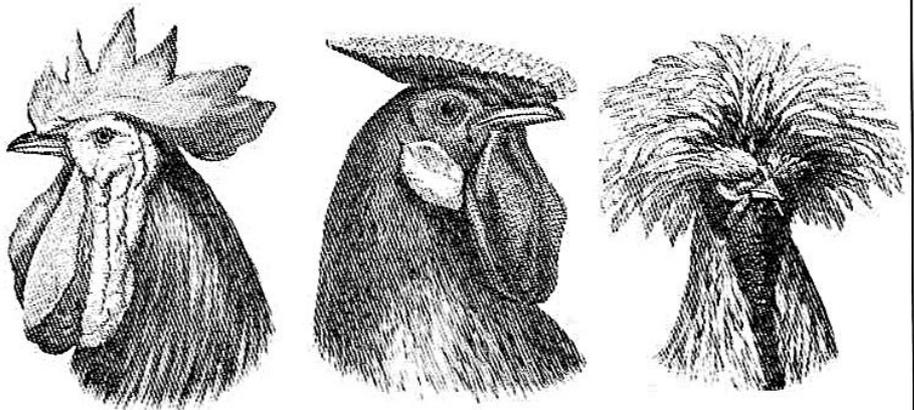


Spanish, Hamburgh and Polish Fowl, illustrated in *Breeds of Animals and Plants under Domestication* by Charles Darwin

# Natural selection



## DARWIN, WALLACE AND EVOLUTION BY NATURAL SELECTION

Charles Darwin developed the theory that evolution occurs as a result of natural selection. He explained his theory in *The Origin of Species*, published in 1859. He had done many years of research and had collected much evidence for the theory before then.

Darwin delayed publication of his ideas for many years, fearing a hostile reaction. He might never have published them if another biologist, Alfred Wallace, had not written a letter to him in 1858 suggesting very similar ideas.

The theory of evolution by natural selection can be explained in a series of observations and deductions.

The photograph on the right shows a statue of Charles Darwin at Shrewsbury School, where he was a pupil from 1818 to 1825.

| Observations | Deductions |
|---|---|
| * Populations of living organisms tend to increase exponentially<br>* Yet, on the whole, the number of individuals in populations remains nearly constant | * More offspring are produced than the environment can support<br>* There is a struggle for existence in which some individuals survive and some die |
| * Living organisms vary. The members of a species are different from each other in many ways<br>* Some individuals have characteristics that make them well adapted to their environment and other individuals have characteristics that make them less well adapted to their environment | * The better adapted individuals tend to survive and reproduce more than the less well-adapted individuals<br>**This is natural selection** |
| * Much variation is heritable – it can be passed on to offspring | * The better-adapted individuals pass on their characteristics to more offspring than the less well adapted individuals. The results of natural selection therefore accumulate<br>* As one generation follows another, the characteristics of the species gradually change – the species evolves |

In 1828 Darwin, as a young man was struggling to learn enough mathematics to pass a university exam. The extract below is from a letter that he wrote to Charles Whitley, a friend and eminent mathematician.

' I am as idle as idle can be: one of the causes you have hit on, viz irresolution the other being made fully aware that my noddle is not capacious enough to retain or comprehend Mathematics. – Beetle hunting & such things I grieve to say is my proper sphere...'

# Evolution in action

## ENVIRONMENTAL CHANGE AND EVOLUTION

Since Darwin developed his theory of evolution by natural selection, changes have been observed in some species. In each case, the evolution has been in response to environmental change.

Two examples are described here – the development of antibiotic resistance in bacteria and melanism in ladybugs. Other examples include the development of metal tolerance in plants growing on waste material from mining metal ores, and changes to the beaks of finches on the Galápagos Islands in response to El Niño events.

All these recent cases of observed evolution involve relatively small changes, but they do nonetheless add to the evidence for evolution.

## SEXUAL REPRODUCTION AND EVOLUTION

Variation is essential for natural selection and therefore for evolution. Although mutation is the original source of new genes or alleles, sexual reproduction promotes variation by allowing the formation of new combinations of alleles. Two stages in sexual reproduction promote variation.

1. Meiosis allows a huge variety of genetically different gametes to be produced by each individual.
2. Fertilization allows alleles from two different individuals to be brought together in one new individual.

Prokaryotes do not reproduce sexually but have other ways to promote variation by exchanging genes.

Some species of organisms only reproduce asexually. Mutations still produce some variation in these species, but without sexual reproduction the variation and the capacity for evolution is less.

## Multiple antibiotic resistance in bacteria

Antibiotics are used to control diseases caused by bacteria in humans. There have been increasing problems with disease-causing bacteria being resistant to antibiotics. The figure below shows the percentage of cases of gonorrhea (a sexually transmitted disease) in the United States that were caused by antibiotic-resistant strains of *Neisseria gonorrhoeae* between 1980 and 1990. The trend with many other diseases has been similar.
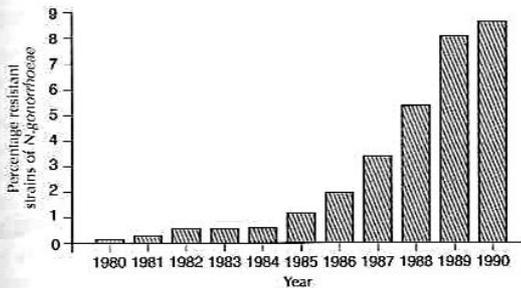


Genes that give resistance to an antibiotic can be found in the micro-organisms that naturally make that antibiotic. The evolution of multiple antibiotic resistance involves the following steps.

- A gene that gives resistance to an antibiotic is transferred to a bacterium by means of a plasmid or in some other way. There is then variation in this type of bacterium – some of the bacteria are resistant to the antibiotic and some are not.
- Doctors or vets use the antibiotic to control bacteria. Natural selection favours the bacteria that are resistant to it and kills the non-resistant ones.
- The antibiotic-resistant bacteria reproduce and spread, replacing the non-resistant ones. Eventually, most of the bacteria are resistant.
- Doctors or vets change to a different antibiotic to control bacteria. Resistance to this soon develops, so another antibiotic is used, and so on until multiply resistant bacteria have evolved.

The more an antibiotic is used, the more bacteria resistant to it there will be and the fewer non-resistant.

## Evolution of melanism in ladybugs

*Adalia bipunctata*, the two-spot ladybug (or ladybird), is a small beetle, which usually has red wing cases with two black spots. The red colour warns predators that it tastes unpleasant. Melanic forms also exist, with black wing cases. The melanic form absorbs heat more efficiently than the red form. It therefore has a selective advantage when sunlight levels are low and it is difficult for ladybugs to warm up. The melanic form of *Adalia bipunctata* became common in industrial areas of Britain, but declined again after 1960. The decline correlates with decreases in smoke in the air (below). In air darkened by smoke, the melanic forms will be able to warm up more quickly, but if the smoke is no longer present this advantage is lost and warning colouration is more important.
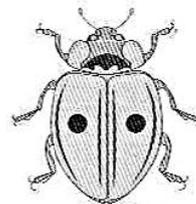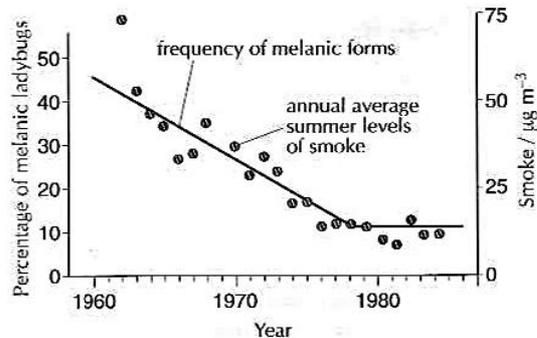


*Adalia 2-punctata*
(f. *typica*)
2-spot ladybird (typical)
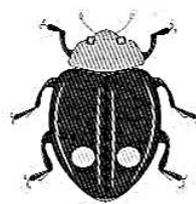
*Adalia 2-punctata*
(f. *quadrimaculata*)
2-spot ladybird (melanic)

# Trophic levels

Populations do not live in isolation – they live together with other populations in **communities**. *A community is a group of populations living together and interacting with each other in an area.*

There are many types of interaction between populations in a community. Trophic relationships are very important – where one population of organisms feeds on another population. Sequences of trophic relationships, where each member in the sequence feeds on the previous one, are called **food chains**.

**An example from rainforest at Iguazu in north-east Argentina.**



| Passionflower (*Passiflora schummaniana*) | → | Heliconius butterfly (*Heliconius erato*) | → | tegu lizard (*Tupinambis teguixin*) | → | jaguar (*Panthera onca*) |
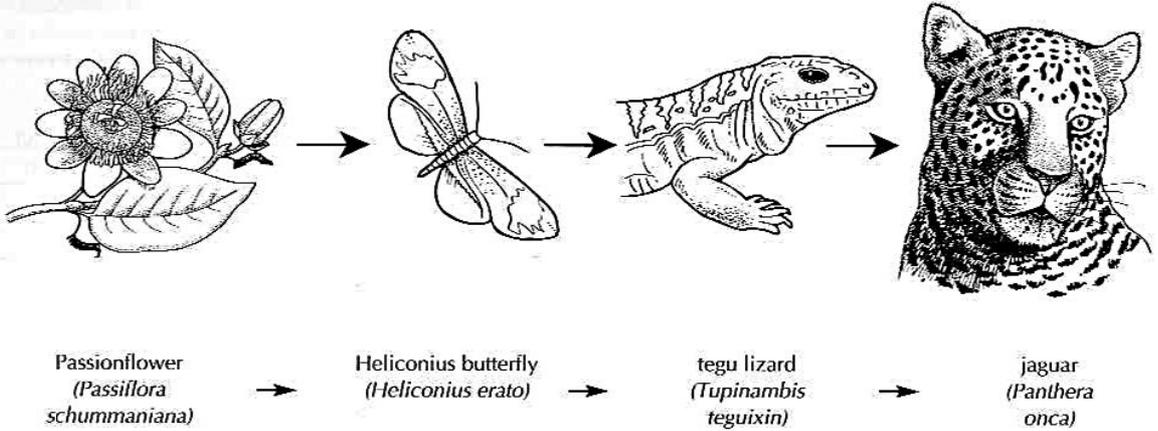
**An example from chalk grassland and the air above it in Europe.**



carrot plant → carrot fly → flycatcher → sparrowhawk → goshawk
(*Daucus carota*) (*Psila rosea*) (*Muscicapa striata*) (*Accipiter nisus*) (*Accipiter gentilis*)
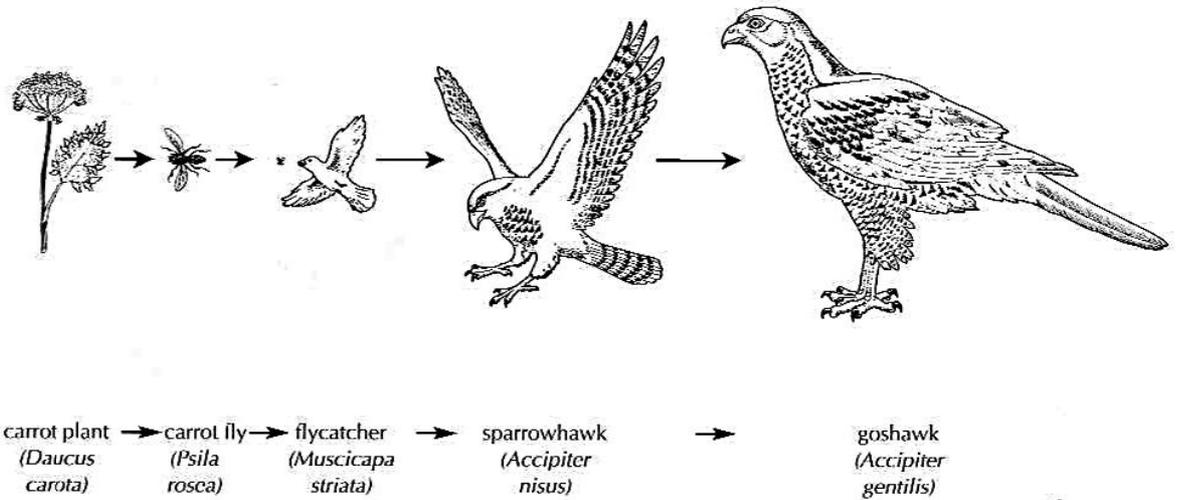
The first organism in a food chain does not feed on other organisms so must be a producer – an organism that makes its own food. The other organisms are all consumers and are called primary, secondary, tertiary and so on, depending on their position in the chain.

Producer, primary consumer, secondary consumer and tertiary consumer are examples of **trophic levels**. *The trophic level of an organism is its position in the food chain.*

**Example:**

| **Producer** | → | **Primary consumer** | → | **Secondary consumer** | → | **Tertiary consumer** |
| Sea lettuce (*Ulva lactuca*) | | Marine iguana (*Amblyrhyncus cristatus*) | | Galapagos snake (*Dromiscus biserialis*) | | Galapagos hawk (*Buteo galapagensis*) |
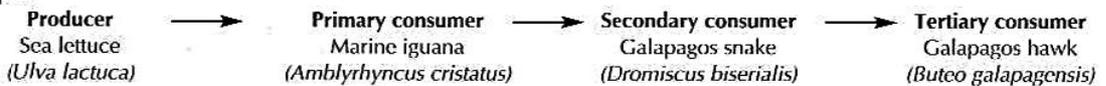
A food chain shows only some of the trophic relationships in a community. Organisms rarely feed on only one other organism and are usually fed on by more than one organism. The complex network of trophic relationships in a community is shown in full in a complex diagram called a food web. An example of a food web is shown on page 42.

# Energy flow

## AUTOTROPHS

The organisms in a community all need a supply of energy. Organisms are divided into two groups according to their source – **autotrophs** and **heterotrophs**.

*Autotrophs are organisms that synthesize their own organic molecules (food) from simple inorganic substances.*

Autotrophs make their own food, so are also called producers. Oak trees, maize plants, algae, blue-green bacteria are examples. All food chains start with a producer. In almost all communities, the producers make organic matter by photosynthesis.

Light is therefore the **initial energy source** for the whole community. Producers convert light energy into the chemical energy of sugars and other organic compounds. This energy trapped by the producers eventually leaves them in one of three ways, shown in the flow chart (right).

**Energy flow through producers**
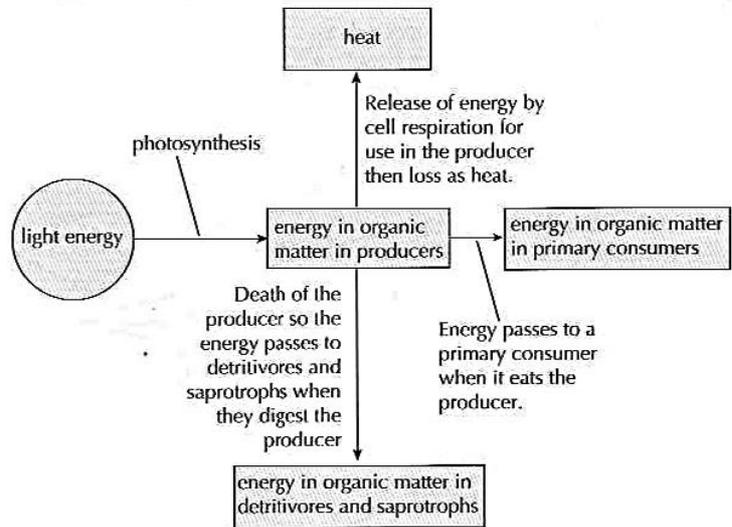


## HETEROTROPHS

*Heterotrophs are organisms that obtain organic molecules (food) from other organisms.*

There are three types of heterotroph: **consumers, detritivores** and **saprotrophs**.

*Consumers are organisms that ingest organic matter that is living or recently killed.* Primary consumers eat producers and so obtain energy from them. They do not absorb all of the energy in the food that they eat. The energy that they do not take into their tissues leaves them in one of three ways, shown in the flow chart (right). There are similar energy losses from secondary and tertiary consumers in the food chain. Locusts, sheep and lions are examples of consumers.

*Detritivores ingest dead organic matter.* Dung beetles and earthworms are examples of detritivores.

*Saprotrophs live on or in dead organic matter, secreting enzymes into it and absorbing the products of digestion.* Bread mould and mushrooms are examples of saprotrophs.

The energy that passes to detritivores and saprotrophs is eventually released by cell respiration and lost as heat. In most communities all the light energy that was trapped by producers is ultimately lost as heat after flowing through the food chain. A summary of energy flow for a three-stage food chain is shown (right).

**Energy flow through consumers**
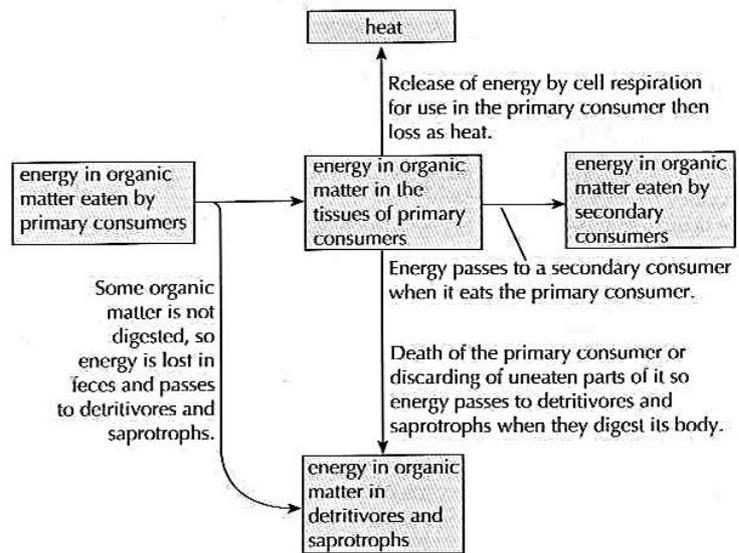


**Energy flow through a food chain**
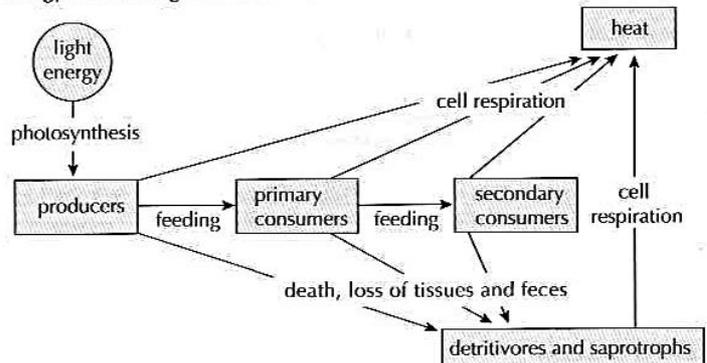
# Food webs and energy pyramids

## FOOD WEBS

A food web is a diagram that shows all the feeding relationships in a community. The arrows indicate the direction of energy flow. Complete food web diagrams are very complex. The figure (below) shows a simplified food web for a community that lives in an area of Arctic tundra in Ogotoruk Valley.

**Food web for Arctic tundra**
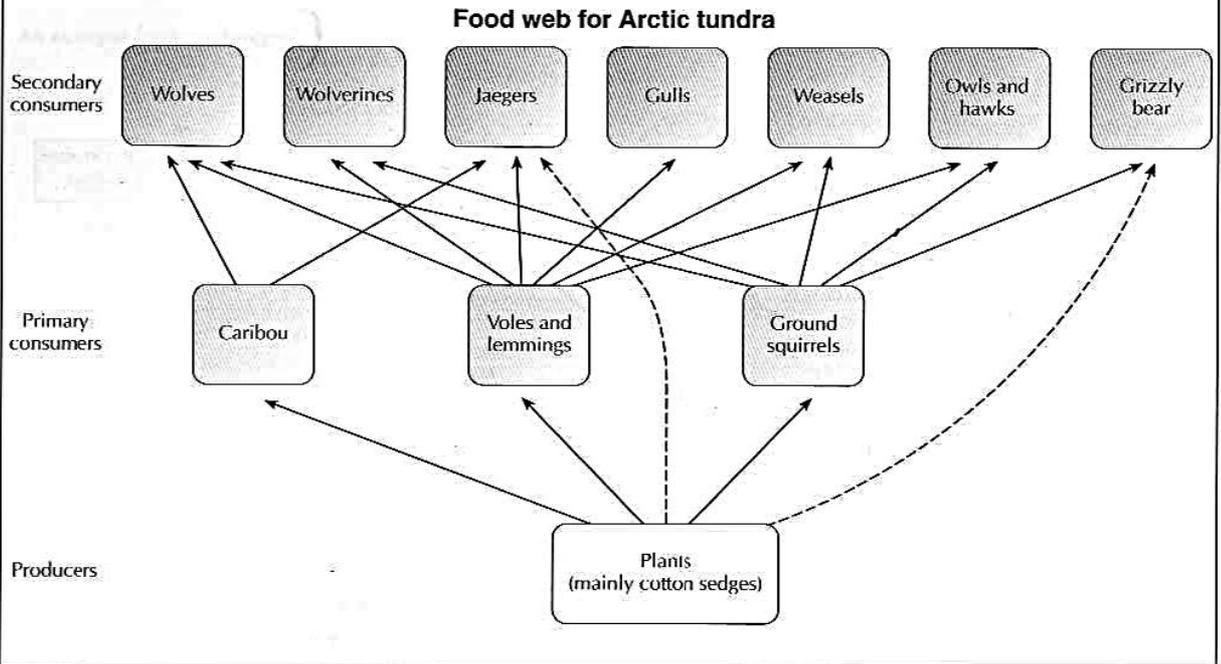


## ENERGY PYRAMIDS

Energy pyramids are diagrams that show how much energy flows through each trophic level in a community. The amounts of energy are shown per square metre of area occupied by the community and per year ($kJ\,m^{-2}\,year^{-1}$). The figure (right) is a pyramid of energy for Silver Springs, a stream in Florida.

The figure (below right) is a pyramid of energy for a salt marsh in Georgia. Pyramids of energy are always pyramid shaped – each level is smaller than the one below it. This is because less energy flows through each successive trophic level. Energy is lost at each trophic level, so less remains for the next level. Note that mass is lost as well as energy, so the energy content per gram of the tissues of each successive trophic level is *not* lower.

Energy is lost in various ways. In each of the first three ways the energy is not completely lost from the community as it passes to detritivores and saprotrophs.
- Some organisms die before an organism in the next trophic level eats them.
- Some parts of organisms such as bones or hair are not eaten.
- Some parts of organisms are indigestible and pass out as feces.
- Much of the energy absorbed by an organism is released in cell respiration. The energy, in the form of ATP, is used in processes such as muscle contraction or active transport that require energy. These processes involve energy transformations, which are never 100% efficient. Some of the energy is converted to heat. 10–20% is a typical efficiency level. Most of the energy released by cell respiration is lost from the organism as heat.

Energy absorbed by living organisms is only available to the next trophic level if it remains as chemical energy in the growth of the organism. This is only a small proportion of the energy absorbed.

**Energy pyramid for a stream**



| trophic level | value |
|---|---|
| tertiary consumers | 67 |
| secondary consumers | 1602 |
| primary consumers | 14 000 |
| producers | 87 000 |
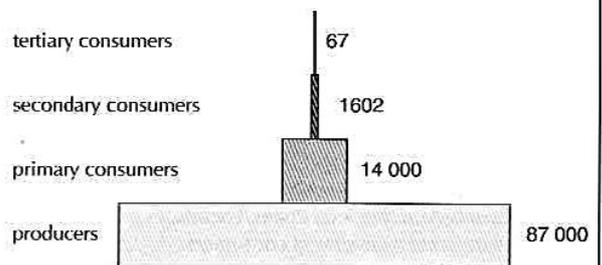
**Energy pyramid for a salt marsh**



| trophic level | value |
|---|---|
| secondary consumers | 117 |
| primary consumers | 1278 |
| producers | 152 000 |
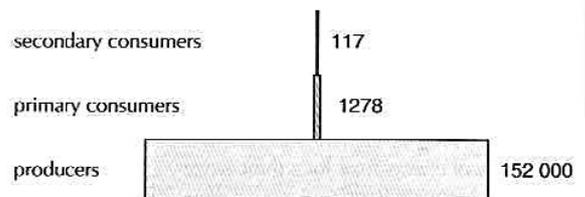
# Nutrient recycling

## ECOSYSTEMS, ECOLOGISTS AND ECOLOGY

Communities of living organisms interact in many ways with the soil, water and air that surround them. The non-living surroundings of a community are its abiotic environment. A community and its **abiotic environment** function together as a system called an **ecosystem**. *An ecosystem is a community and its abiotic environment.*
Ecologists study the complex relationships within ecosystems. This area of study is called **ecology**. *Ecology is the study of relationships in ecosystems – both relationships between organisms and between organisms and their environment.*

## NUTRIENT RECYCLING IN ECOSYSTEMS

The recycling of nutrients is one example of the interactions between living organisms and the abiotic environment in an ecosystem. Energy is not recycled. It is supplied to ecosystems in the form of light, flows through food chains and is lost as heat. Nutrients are not usually resupplied to ecosystems – they must be used again and again by recycling. Carbon, nitrogen, phosphorus and all the other essential elements must be recycled. They are absorbed from the environment, used by living organisms and then returned to the environment.
The processes involved in the carbon cycle are shown below.

## The carbon cycle
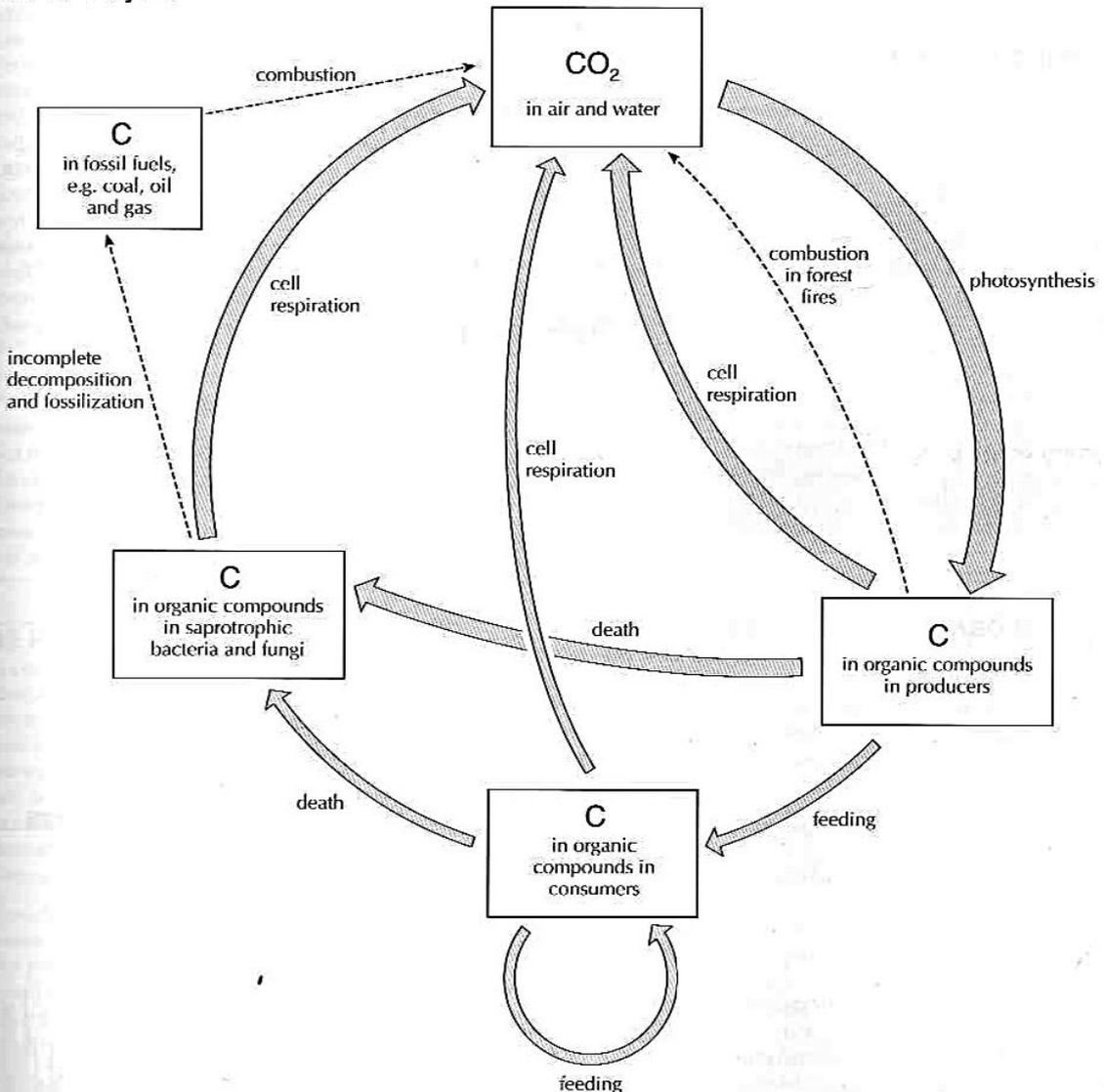


## THE ROLE OF SAPROTROPHS IN RECYCLING OF NUTRIENTS

Saprotrophic bacteria and fungi have an essential role in nutrient cycles. They feed by secreting digestive enzymes into dead organic matter, including dead plants and animals and feces. The enzymes gradually break down the organic matter and the nutrients that were locked up in complex organic compounds are released. The saprotrophs absorb the substances that they need from the digested organic matter.
Without saprotrophs, nutrients would remain locked up permanently in dead organic matter and organisms that need the nutrients would soon become deficient.

# Global warming and the greenhouse effect

## RISING CARBON DIOXIDE LEVELS

The carbon dioxide concentration of bubbles of air trapped in Antarctic ice at different dates have been measured. These show that for two thousand years before 1880 the carbon dioxide concentration of the atmosphere remained fairly constant at about 270 parts per million (ppm).

From 1880 onwards the concentration rose. Since 1958, the concentration has been monitored continuously at Mauna Loa, Hawaii (right). There is an annual fluctuation, but the overall trend has been upwards and the concentration is now more than 100ppm higher than in 1880.

## GREENHOUSE GASES

Carbon dioxide is one of a group of gases that cause heat to be retained in the Earth's atmosphere:
- carbon dioxide
- methane
- oxides of nitrogen (NOX)
- sulfur dioxide

Heat retention by gases is called the **greenhouse effect**. The processes involved are shown in the figure (right).

The greenhouse effect is not a new phenomenon. Natural processes produce greenhouse gases, so they are a natural part of the Earth's atmosphere. The change in recent years is that human activities have increased the production of greenhouse gases and so their atmospheric concentrations and their contributions to the greenhouse effect have been rising (below right). This is correlated with rising temperatures on Earth – **global warming**.

## RISING GLOBAL TEMPERATURES

Temperature records have been analysed to find the mean for the whole world in each year from 1850 onwards. The figure (right) shows the difference between the mean temperature for each year and an overall mean temperature for the years 1961–1990.

The trends are that
- From 1856 until about 1910 temperatures were relatively stable.
- From 1910 until 1940 temperatures rose and were then stable.
- From 1970 there has been a rapid rise.
- All ten of the hottest years since records began in 1850 have been since 1990.
- 1998 was the hottest year in that period and 2005 was the second hottest year.
- Over the past century, global temperatures have risen by 0.7°C on average, which takes us out of the range of average temperatures experienced on Earth over the last 1000 years.

These changes in temperature are statistically significant. There could be various causes, but the most likely cause is an increased greenhouse effect, due to human activities.

**Graph of atmospheric $CO_2$ concentrations**



Mauna Loa observatory, Hawaii monthly average carbon dioxide concentration

**Cause of the greenhouse effect**



Light from the sun has short wavelengths and can mostly pass through the atmosphere

Greenhouse gases in the atmosphere including $CO_2$, methane, water vapour and sulfur dioxide trap some of the long-wave radiation, causing the Earth to be warmer than if the radiation escaped.

Sunlight warms up the surface of the Earth which emits long-wave radiation

**Increases in effects of greenhouse gases**



Increase in the warming effect of the gas between 1750 and 2000 / Wm$^{-2}$

$CO_2$   $CH_4$   halo carbons   $N_2O$

**Annual global temperatures 1850–2005**



— Annual average
— Long-term trend
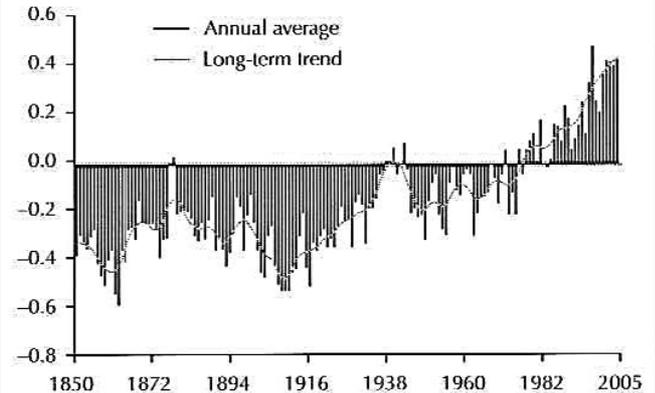
# Responses to global warming

## HABITATS

The Earth provides places for millions of living organisms to exist. These places are called **habitats**.

*A habitat is the environment in which a species normally lives or the location of a living organism.*

## CONSEQUENCES OF GLOBAL WARMING

The effects of global warming are already being felt, but they are likely to become much more extreme during the 21$^{st}$ century. Habitats throughout the world will be affected, but the effects on Arctic ecosystems could be particularly catastrophic.

- Glaciers will melt and polar ice sheets will break up into icebergs, which will also eventually melt. The Arctic ice cap may disappear completely.
- Permafrost will melt during the summer, increasing the rates of decomposition of trapped organic matter, including peat and detritus. This will cause release of carbon dioxide, further increasing atmospheric concentrations.
- Species adapted to temperate conditions will spread north, altering food chains and affecting animals in the higher trophic levels.
- Marine species of animal in Arctic waters may become extinct, as they can be very sensitive to temperature changes in seawater.
- Polar bears and other animals will lose their ice habitat, where they feed and breed.
- Pests and diseases may become more prevalent, with warmer temperatures.
- Sea levels will rise and low-lying areas of land will be flooded.
- Extreme weather events, such as storms, will become more frequent, with harmful effects on species that are not adapted.

## THE PRECAUTIONARY PRINCIPLE

In a court of law, prosecutors try to prove that the defendant is guilty. If they cannot do this, the defendant is assumed to be innocent. When the precautionary principle is followed, the opposite policy is adopted – people planning to do something must prove that it will *not* do harm, before actually doing it. The precautionary principle should be followed when the possible consequences (risks) of human actions are very large or could even be catastrophic.

Although there is strong evidence that greenhouse gas emissions are causing global warming, there is no proof. Some politicians and business leaders have argued against measures to combat global warming, because it is not *certain* that greenhouse gases are causing it. Oil companies and airlines in particular have voiced opposition.

Many scientists have argued that if we waited for proof of the effects of greenhouse gas emissions before reacting, the consequences would probably have reached a catastrophic level. The risks are so great that the precautionary principle should be followed: anyone advocating continuing to emit greenhouse gases at current levels, or even to increase emissions, should be required to prove that this will not cause a damaging increase in the greenhouse effect.
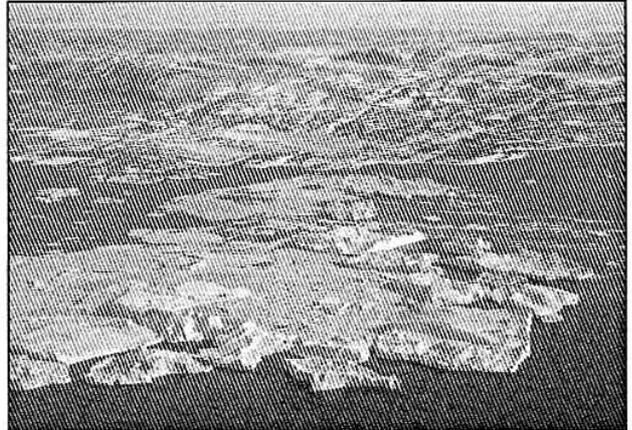


**Ice sheet breaking up, with Greenland in the background**



Musk ox (*Ovibos moschatus*) a species of mammal which nearly became extinct through over-hunting in the early 20$^{th}$ century. Protection by the Canadian government has allowed them to increase, with the population now over 60 000. They have a very thick coat and are adapted to the cold conditions of Arctic regions. The consequence of global warming for musk ox can be deduced from the distribution map (below).
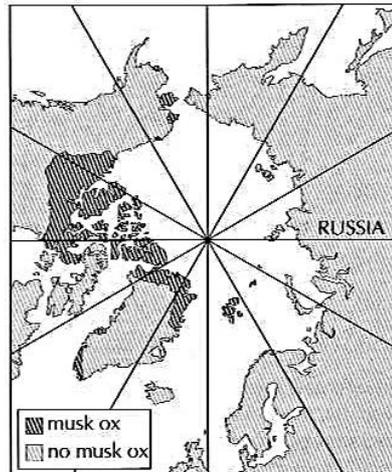


- musk ox
- no musk ox

**Distribution map of musk ox in the Arctic**

# EXAM QUESTIONS ON TOPIC 5

1 The graph below shows the growth of a population of ring-necked pheasants (*Phasianus colchicus*) on Protection Island off the north west coast of the United States. The original population released by the scientists consisted of two male and eight female birds. Two of the females died immediately after release.
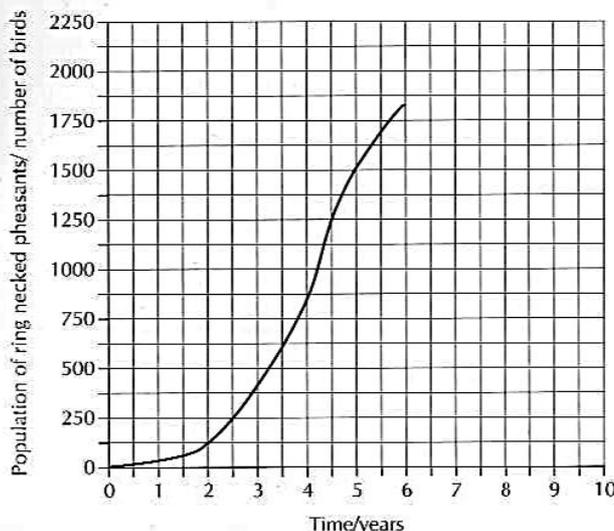


[Source of data: Elinarson A. S., Murrelet, (1945) 26: pages 39–44]

a) State the term used to describe the shape of a growth curve of this type. [1]

b) (i) The scientists predicted that the population would reach its carrying capacity of 2000 by year 8.
   Draw a line on the graph to show the population growth between years 6 and 10. [2]

c) (i) Predict how the population growth would change if all the female birds in the original sample had survived. [1]

   (ii) Predict the effect on the carrying capacity if all the female birds in the original sample had survived. [1]

2 The diagram below shows in simplified form the transfers of energy in a generalized ecosystem.
Each box represents a category of organisms, grouped together by their trophic position in the ecosystem.
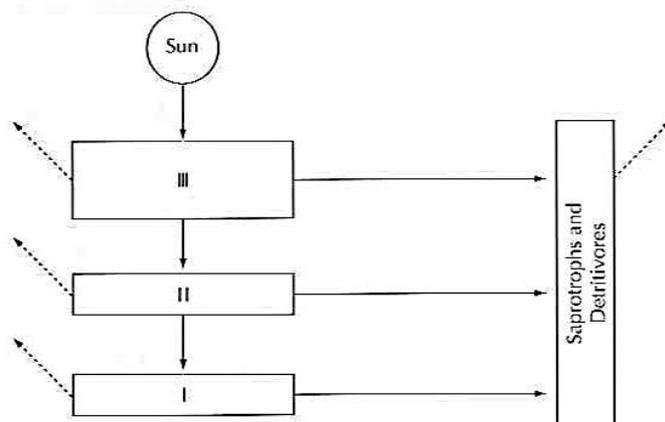


a) Deduce the trophic levels of the organisms in boxes I, II and III. [3]

b) State the form in which energy enters organisms in box 1. [1]

c) Identify which arrow represents the greatest transfer of energy per unit of time. (Add a large X to the arrow). [1]

d) Explain what is represented by the dotted arrows leaving each box. [3]

3 Methane acts as a greenhouse gas in the atmosphere. The main sources of methane are the digestive systems of cattle and sheep, bacterial action in rice paddies, burning of biomass (e.g. forest fires), bacterial action in swamps and marshes, burning of coal and release of natural gas.

a) Discuss whether methane emissions from these sources will cause a change in the Earth's temperature. [3]

b) Discuss whether release of methane is a natural process or an example of a human impact on the environment. [3]

c) Suggest measures that could be taken to reduce the emission of methane. [3]

# Digestion

## TAKING IN FOOD

Humans take food into their digestive system through the mouth and the esophagus. However, this food is not truly inside the body until it has passed through a layer of cells into the body's tissues. This happens in the small intestines and is called **absorption**. Small finger-like projections from the wall of the small intestine called villi are specially adapted to absorb food molecules. The structure of a villus is shown below. After food has been absorbed it is **assimilated** – it becomes part of the tissues of the body.

### Structure of a villus



- epithelium
- layer of microvilli on surface of epithelium
- blood capillary
- lacteal (a branch of the lymphatic system)
- goblet cells (secrete mucus)
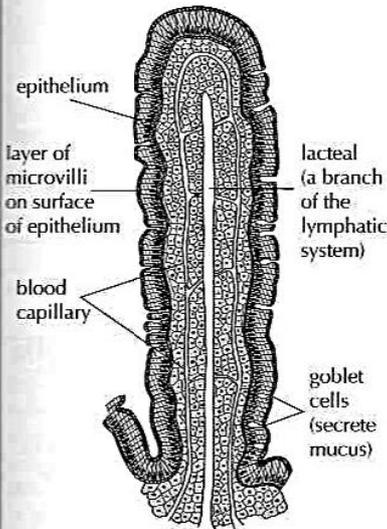
## RELATIONSHIP BETWEEN STRUCTURE OF A VILLUS AND ITS FUNCTION

- Villi increase the surface area over which food is absorbed.
- An epithelium, consisting of only one thin layer of cells, is all that foods have to pass through to be absorbed.
- Protrusions of the exposed part of the plasma membranes of the epithelium cells increase the surface area for absorption. These projections are called microvilli.
- Protein channels in the microvilli membranes allow rapid absorption of foods by facilitated diffusion and pumps allow rapid absorption by active transport.
- Mitochondria in epithelium cells provide the ATP needed for active transport.
- Blood capillaries inside the villus are very close to the epithelium so the distance for diffusion of foods is very small.
- A lacteal (a branch of the lymphatic system) in the centre of the villus carries away fats after absorption.

## THE NEED FOR DIGESTION

The food that humans eat contains substances made by other organisms, many of which are not suitable for human tissues. They must therefore be broken down and reassembled in a form that is suitable.

A second reason for digestion is that many of the molecules in foods are too large to be absorbed by the villi in the small intestine. These large molecules have to be broken down into small molecules that can then be absorbed by diffusion, facilitated diffusion or active transport. The three main types of food molecule that need to be digested are starch, protein and triglycerides (fats and oils).

Digestion of these large molecules happens naturally at body temperature, but only at a very slow rate. Enzymes are essential to speed up the process.

### Enzymes of digestion

|  | Amylase | Protease | Lipase |
|---|---|---|---|
| **Example of this enzyme** | Salivary amylase | Pepsin | Pancreatic lipase |
| **Source** | Salivary glands | Wall of stomach | Pancreas |
| **Substrate** | Starch | Proteins | Triglycerides (fats or oils) |
| **Products** | Maltose | Small polypeptides | Fatty Acids and Glycerol |
| **Optimum pH** | pH 7 | pH 1.5 | pH 7 |

### The human digestive system



- mouth
- esophagus
- liver
- gall bladder
- small intestine
- stomach
- pancreas
- large intestine (part not shown)
- anus
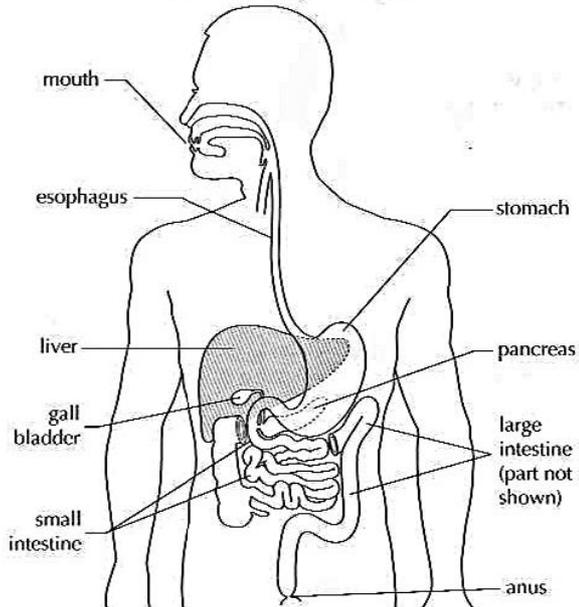
## FUNCTIONS OF THE STOMACH AND INTESTINES

Digestion of proteins begins in the stomach, catalysed by pepsin. Bacteria, which could cause food poisoning, are mostly killed by the acid conditions of the stomach. The acidity also provides optimum conditions for pepsin to work.

Enzymes secreted by the wall of the small intestine complete the process of digestion. The end products of digestion are absorbed by the villi protruding from the wall of the small intestine.

The indigestible parts of the food, together with a large volume of water, pass on into the large intestine. Water is absorbed here leaving solid feces, which are eventually egested through the anus.

# The cardiovascular system

## HEART STRUCTURE

The heart is a double pump, with the right side pumping blood to the lungs and the left side pumping blood to all other organs. The walls of the heart are composed of cardiac muscle. Contraction of cardiac muscle is **myogenic** – it can contract on its own, without being stimulated by a nerve. There are many capillaries in the muscular wall of the heart. The blood running through these capillaries is supplied by the coronary arteries, which branch off the aorta, close to the semilunar valve. The blood brought by the coronary arteries brings nutrients. It also brings oxygen for aerobic cell respiration, which provides the energy needed for cardiac muscle contraction.

## Structure of the heart



aorta
pulmonary arteries
vena cava (superior)
right atrium
semilunar valves
vena cava (inferior)
atrio-ventricular valve
right ventricle
left atrium
pulmonary veins
atrio-ventricular valve
left ventricle
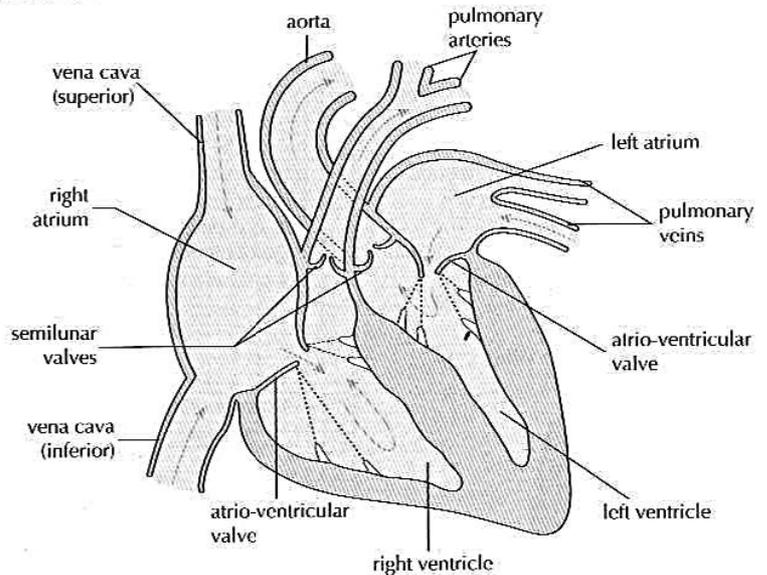
## BLOOD VESSELS

### Arteries

Thick outer layer of longitudinal collagen and elastic fibres to avoid bulges and leaks

Thick wall to withstand the high pressures
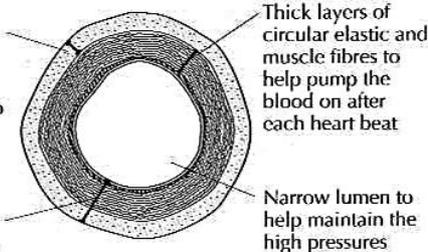
Thick layers of circular elastic and muscle fibres to help pump the blood on after each heart beat

Narrow lumen to help maintain the high pressures

### Veins

Thin layers with a few circular elastic and muscle fibres because blood does not flow in pulses so the veins wall cannot help pump it.

Wide lumen is needed to accomodate the slow-flowing blood
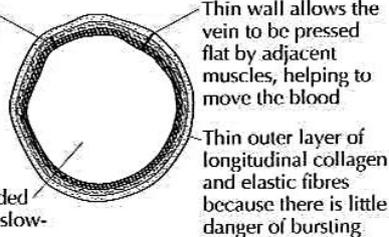
Thin wall allows the vein to be pressed flat by adjacent muscles, helping to move the blood

Thin outer layer of longitudinal collagen and elastic fibres because there is little danger of bursting

N.B. veins have valves to prevent back-flow

### Capillaries

Wall consists of a single layer of thin cells so the distance for diffusion in or out is small.

Pores between cells in the wall allow some of the plasma to leak out and form tissue fluid. Phagocytes can also squeeze out.
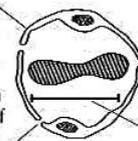
Very narrow lumen – only about 10µm across so that capillaries fit into small spaces. Many small capillaries have a larger surface area than fewer wider ones

## THE ACTION OF THE HEART

The atria are the collecting chambers – they collect blood from the veins. The ventricles are the pumping chambers – they pump blood out into the arteries at high pressure. The valves ensure that the blood always flows in the correct direction. Every heartbeat consists of a sequence of actions.

1. The walls of the atria contract, pushing blood from the atria into the ventricles through the atrioventricular valves, which are open. The semilunar valves are closed, so the ventricles fill with blood.

2. The walls of the ventricles contract powerfully and the blood pressure rapidly rises inside them. This rise in pressure first causes the atrioventricular valves to close, preventing back-flow of blood to the atria and then causes the semilunar valves to open, allowing blood to be pumped out into the arteries. At the same time the atria start to refill as they collect blood from the veins.

3. The ventricles stop contracting and as pressure falls inside them the semilunar valves close, preventing back-flow of blood from the arteries to the ventricles. When the ventricular pressure drops below the atrial pressure, the atrioventricular valves open. Blood entering the atrium from the veins then flows on to start filling the ventricles. The next heartbeat begins when the walls of the atria contract again.

## THE CONTROL OF THE HEART BEAT

Heart muscle tissue has a special property – it can contract on its own without being stimulated by a nerve. One region is responsible for initiating each contraction. This region is called the pacemaker and is located in the wall of the right atrium. Each time the **pacemaker** sends out a signal the heart carries out a contraction or beat. Nerves and hormones can transmit messages to the pacemaker.

• One nerve carries messages from the brain to the pacemaker that tell the pacemaker to speed up the beating of the heart.

• Another nerve carries messages from the brain to the pacemaker that tell the pacemaker to slow down the beating.

• Adrenalin, carried to the pacemaker by the bloodstream, tells the pacemaker to speed up the beating of the heart.

# Blood, transport and infections

## THE COMPOSITION OF BLOOD

Blood is composed of plasma, erythrocytes (red blood cells), leukocytes and platelets. The figure below shows the appearance of blood as seen using a light microscope. Two types of leukocyte are shown.



lymphocyte

phagocyte

leukocytes (white blood cells)

platelets

plasma transporting nutrients, carbon dioxide, hormones, antibodies and urea

erythrocytes (red blood cells) transporting oxygen
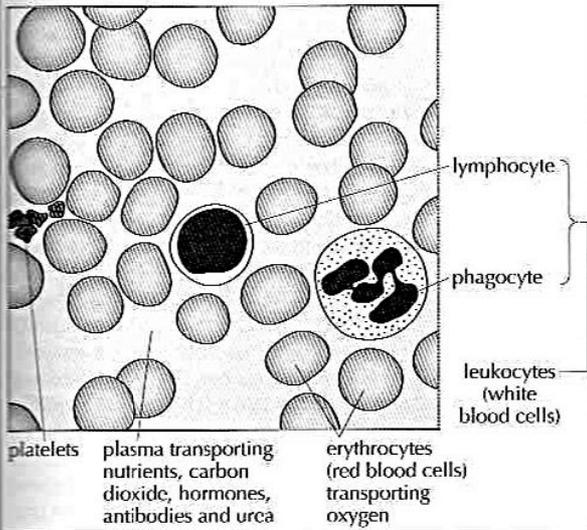
## PHAGOCYTES

Some of the leukocytes in blood are phagocytes. These cells can identify pathogens and ingest them by endocytosis. *A pathogen is an organism or virus that causes disease.* The pathogens are then killed and digested inside the cell by enzymes from lysosomes. Phagocytes can ingest pathogens in the blood. They can also squeeze out through the walls of blood capillaries and move through tissues to sites of infection. They then ingest the pathogens causing the infection. Large numbers of phagocytes at a site of infection form pus.

Some pathogens are able to avoid being killed by phagocytes, so another defence is needed.



pathogens   phagocytic leukocyte   ingested pathogens
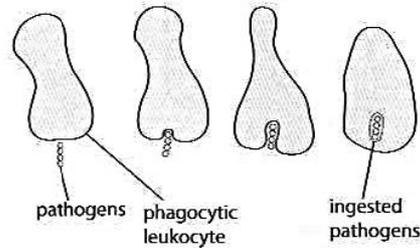
## FUNCTIONS OF BLOOD

Blood has two main functions: transport and defence against infectious disease.

Red blood cells transport oxygen from the lungs to respiring cells.

Blood plasma transports
- nutrients
- carbon dioxide
- hormones
- antibodies
- urea.

The blood also transports heat from parts of the body that produce it, to the skin, where it is lost to the environment. Leukocytes (white blood cells) defend the body against infectious diseases. The roles of phagocytes and leukocytes are described on this page and the next page.

## ANTIBODIES

Antibodies are proteins that recognize and bind to specific antigens. Antigens are foreign substances that stimulate the production of antibodies.

Antibodies usually only bind to one specific antigen. Antigens can be any of a wide range of substances including cell walls of pathogenic bacteria or fungi and protein coats of pathogenic viruses.

Antibodies defend the body against pathogens by binding to antigens on surface of a pathogen and stimulating its destruction. The figure (on page 50) shows how antibodies are produced.



antigen binding site

antigen binding site

Antibody molecule made up of four polypeptides
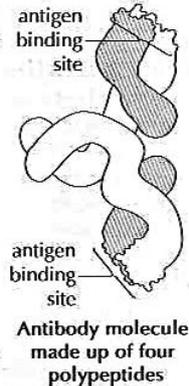
## BARRIERS TO INFECTION

The skin and mucous membranes form a barrier that prevents most pathogens from entering the body. The outer layers of the skin are tough and form a physical barrier. Sebaceous glands in the skin secrete lactic acid and fatty acids, which make the surface of the skin acidic. This prevents the growth of most pathogenic bacteria.

Mucous membranes are soft areas of skin that are kept moist with mucus. Mucous membranes are found in the nose, trachea, vagina and urethra. Although they do not form a strong physical barrier, many bacteria are killed by lysozyme, an enzyme in the mucus. In the trachea pathogens tend to get caught in the sticky mucus and cilia then push the mucus and bacteria up and out of the trachea.

Despite these barriers to infection, pathogens do sometimes enter the body so another defence is needed.

## ANTIBIOTICS

Antibiotics are chemicals produced by microorganisms, to kill or control the growth of other microorganisms. For example, *Penicillium* fungus produces penicillin to kill bacteria.

Most bacterial diseases in humans can be treated successfully with antibiotics. For example, tuberculosis has been treated with streptomycin. There are many differences between human cells and bacterial cells and so there are many antibiotics that block a process in bacterial cells without causing any harm to human cells.

Viruses carry out very few processes themselves. They rely instead on a host cell such as a human cell to carry out the processes for them. It is not possible to block these processes with an antibiotic without also harming the human cells. For this reason virus diseases cannot be treated with antibiotics.

# Antibodies and AIDS

## PRODUCTION OF ANTIBODIES

① Antibodies are made by lymphocytes, one of the two main types of leukocyte.
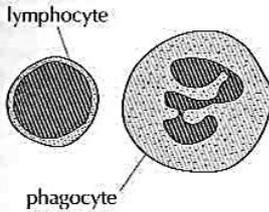
② A lymphocyte can only make one type of antibody so a huge number of different lymphocyte types is needed. Each lymphocyte puts some of the antibody that it can make into its plasma membrane with the antigen-combining site projecting outwards.
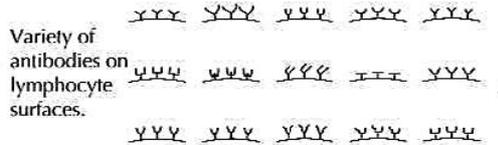
③ When a pathogen enters the body, its antigens bind to the antibodies in the plasma membrane of one type of lymphocyte.

lymphocyte

phagocyte

Variety of antibodies on lymphocyte surfaces.
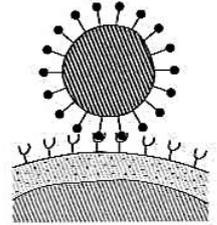
④ When antigens bind to the antibodies on the surface of a lymphocyte, this lymphocyte becomes active and divides by mitosis to produce a clone of many identical cells.

inactive lymphocyte

mitosis

active lymphocyte
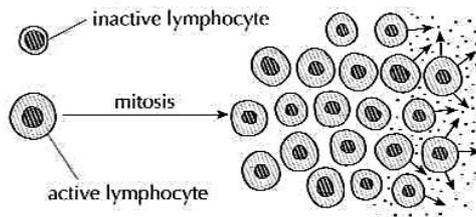
⑤ The clone of cells starts to produce large quantities of the same antibody – the antibody needed to defend the body against the pathogen.

## AIDS – A SYNDROME CAUSED BY A VIRUS

AIDS shows how vital the body's defences against disease are. Destruction of the immune system leads inevitably to death. AIDS is an example of a syndrome. A syndrome is a group of symptoms that are found together. Individuals with acquired immunodeficiency syndrome (AIDS) have low numbers of one type of lymphocyte together with weight loss and a variety of diseases caused by viruses, bacteria, fungi and protozoa. These diseases weaken the body and eventually cause death.

*Cause*
HIV (human immunodeficiency virus) causes AIDS. The virus infects a type of lymphocyte that plays a vital role in antibody production. Over a period of years these lymphocytes are destroyed and antibodies cannot then be produced. Without a functioning immune system, the body is vulnerable to pathogens that would normally be controlled easily.

*Transmission*
HIV does not survive for long outside the body and cannot easily pass through the skin. Transmission involves the transfer of body fluids from an infected person to an uninfected one.
• Through small cuts or tears in the vagina, penis, mouth or intestine during vaginal, anal or oral sex.
• In traces of blood on a hypodermic needle that is shared by intravenous drug abusers.
• Across the placenta from a mother to a baby, or through cuts during childbirth or in milk during breast-feeding.
• In transfused blood or with blood products such as Factor VIII used to treat hemophiliacs.

*Social implications*
• Families and friends suffer grief.
• Families become poorer if the individual with AIDS was the wage earner and is refused life insurance.
• Individuals infected with HIV may become stigmatized and not find partners, housing or employment.
• Sexual activity in a population may be reduced because of the fear of AIDS.

### Structure of HIV

single stranded RNA

reverse transcriptase

lipid bilayer } envelope

glycoprotein

capsid (protein coat)
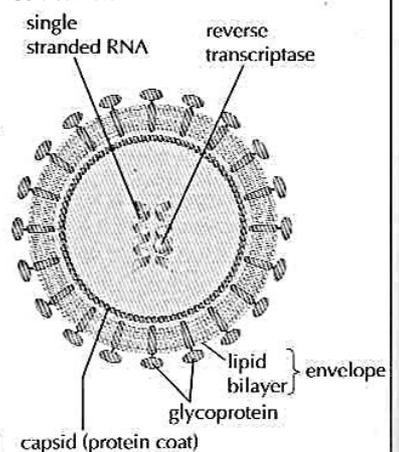
### T-lymphocyte infected with HIV(× 3500)
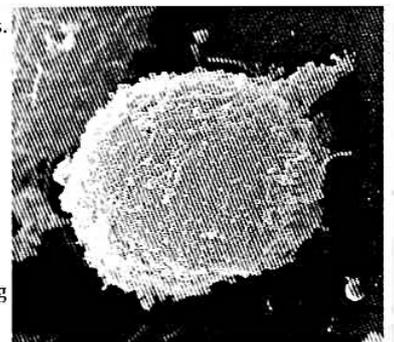
# Gas exchange

## THE NEED FOR GAS EXCHANGE AND VENTILATION IN HUMANS

**Cell respiration** happens in the cytoplasm and mitochondria of cells and releases energy in the form of ATP for use inside the cell. In humans oxygen is used in cell respiration and carbon dioxide is produced. Humans therefore must take in oxygen from their surroundings and release carbon dioxide. This process of swapping one gas for another is called **gas exchange**.

Gas exchange happens in the alveoli of human lungs. Oxygen diffuses from the air in the alveoli to the blood in capillaries. Carbon dioxide diffuses in the opposite direction. The figure (below) shows the adaptations of the alveolus for gas exchange. Diffusion of oxygen and carbon dioxide happens because there are concentration gradients of oxygen and carbon dioxide between the air and the blood. To maintain these concentration gradients, the air in the alveoli must be refreshed frequently. The process of bringing fresh air to the alveoli and removing stale air is called **ventilation**.

## THE VENTILATION SYSTEM



bronchus

intercostal muscles

trachea

left lung

ribs

bronchioles (ending in microscopic alveoli)

diaphragm
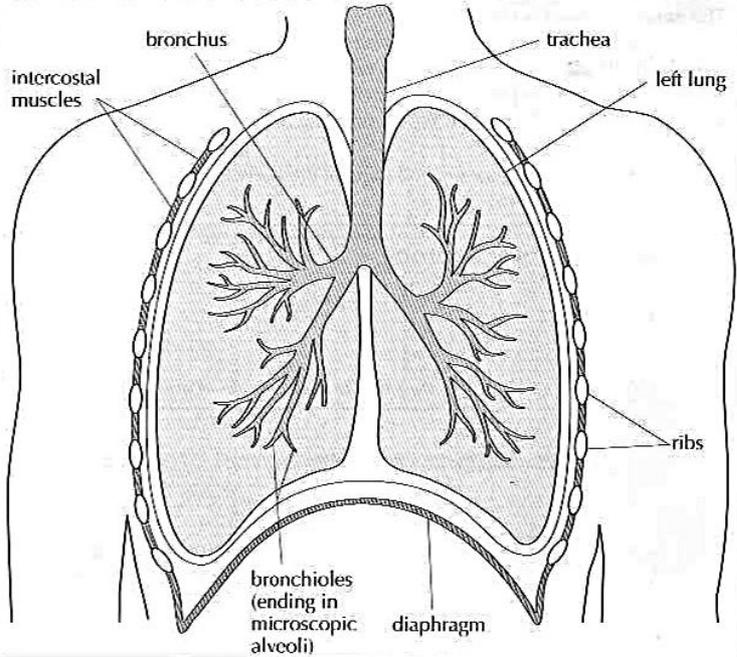
## ADAPTATIONS OF THE ALVEOLUS TO GAS EXCHANGE

Although each alveolus is very small, the lungs contain hundreds of millions of alveoli in total, giving a huge overall surface area for gas exchange.

The wall of the alveolus consists of a single layer of very thin cells. The capillary wall also is a single layer of very thin cells, so the gases only have to diffuse a very short distance.



100 µm
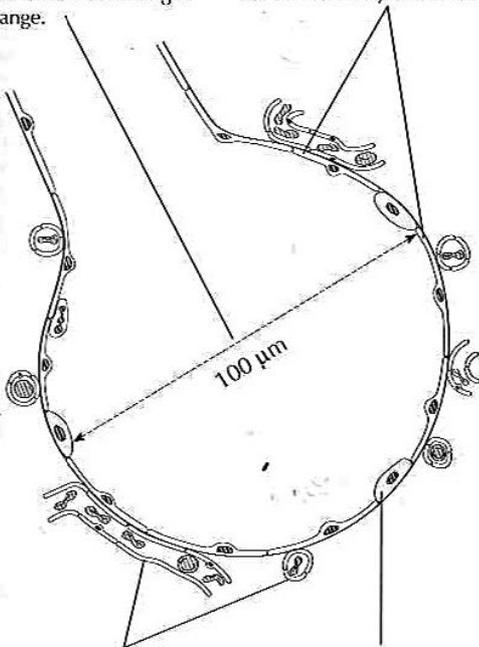
The alveolus is covered by a dense network of blood capillaries with low oxygen and high carbon dioxide concentrations. Oxygen therefore diffuses into the blood and carbon dioxide diffuses out.

Cells in the alveolus wall secrete a fluid which keeps the inner surface of the alveolus moist, allowing the gases to dissolve. The fluid also contains a natural detergent, which prevents the sides of the alveoli from sticking together.

## VENTILATION OF THE LUNGS

Air is inhaled into the lungs through the trachea, bronchi and bronchioles.
It is exhaled via the same route. Muscles are used to lower and raise the pressure inside the lungs to cause the movements of air.

**Inhaling**

- The external intercostal muscles contract, moving the ribcage up and out
- The diaphragm contracts, becoming flatter and moving down
- These muscle movements increase the volume of the thorax
- The pressure inside the thorax therefore drops below atmospheric pressure
- Air flows into the lungs from outside the body until the pressure inside the lungs rises to atmospheric pressure

**Exhaling**

- The internal intercostal muscles contract, moving the ribcage down and in
- The abdominal muscles contract, pushing the diaphragm up into a dome shape
- These muscle movements decrease the volume of the thorax
- The pressure inside the thorax therefore rises above atmospheric pressure
- Air flows out from the lungs to outside the body until the pressure inside the lungs falls to atmospheric pressure

# Neurons and synapses

## ORGANIZATION OF THE NERVOUS SYSTEM

The nervous system is composed of cells called neurons. These cells are often very elongated and can carry messages at high speed in the form of electrical impulses.

There are two parts of the nervous system
- the central nervous system (CNS), consisting of the brain and spinal cord
- peripheral nerves that connect all parts of the body to the central nervous system.

## SENSORY AND MOTOR NEURONS

Neurons carry electrical impulses long distances in the body, using elongated structures called nerve fibres (axons).
- Sensory neurons carry nerve impulses from receptors (sensory cells) to the CNS.
- Motor neurons (below) carry impulses from the CNS to effectors (muscle and gland cells).
- Relay neurons carry impulses within the CNS, from one neuron to another.

## Structure of a motor neuron



motor end plates

direction of transmission of impulse along the axon

nucleus    cell body

axon (nerve fibre)

length of neuron omitted

myelin sheath

nodes of Ranvier

skeletal muscle fibres

dendrites
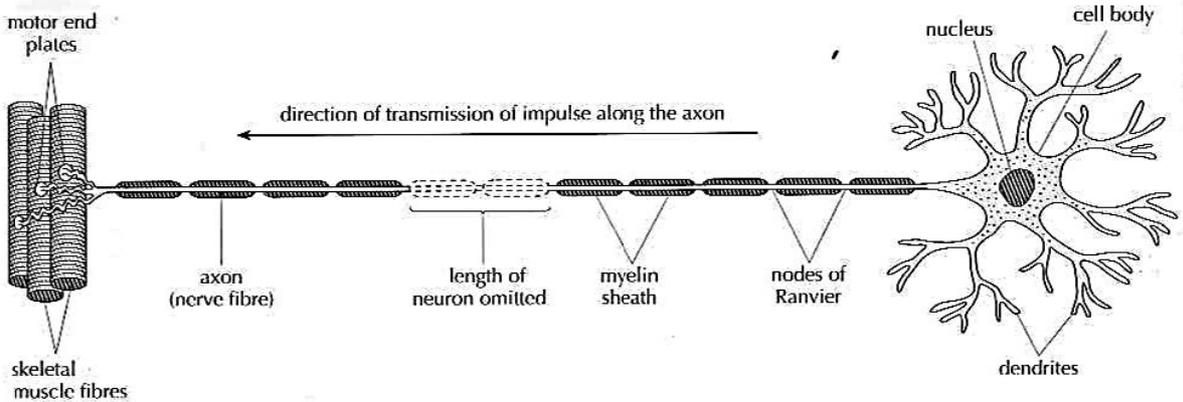
## SYNAPSES

A synapse is a junction between two neurons. The plasma membranes of the neurons are separated by a narrow fluid-filled gap called the synaptic cleft. Messages are passed across the synapse in the form of chemicals called **neurotransmitters**. The neurotransmitters always pass in the same direction from the pre-synaptic neuron to the post-synaptic neuron.

Many synapses function in the following way.
1. A nerve impulse reaches the end of the pre-synaptic neuron.
2. Depolarization of the pre-synaptic membrane causes voltage-gated calcium channels to open. Calcium ions diffuse into the pre-synaptic neuron.
3. Influx of calcium causes vesicles of neurotransmitter to move to the pre-synaptic membrane and fuse with it, releasing the neurotransmitter into the synaptic cleft by exocytosis.
4. The neurotransmitter diffuses across the synaptic cleft and binds to receptors in the post-synaptic membrane.
5. The receptors are transmitter-gated ion channels, which open when neurotransmitter binds. Sodium and other positively charged ions diffuse into the post-synaptic neuron. This causes depolarization of the post-synaptic membrane.
6. The depolarization passes on down the post-synaptic neuron as an action potential.
7. Neurotransmitter in the synaptic cleft is rapidly broken down, to prevent continuous synaptic transmission. For example, acetylcholine is broken down by cholinesterase in synapses that use it as a neurotransmitter. Calcium ions are pumped out of the pre-synaptic neuron into the synaptic cleft.

The figure (right) shows the events that occur during synaptic transmission.

## Stages in synaptic transmission



1. Nerve impulse reaches the end of the pre-synaptic neuron

3. Vesicles of neurotransmitter move to the membrane and release their contents

7. Calcium is pumped out. Neurotransmitter is broken down in the cleft and reabsorbed into the vesicles

synaptic knob

vesicles of neuro-transmitter

2. Calcium diffuses in through calcium channels

$Ca^{2+}$   $Ca^{2+}$

$Ca^{2+}$   $Ca^{2+}$

$Na^+$   $Na^+$   $Na^+$

4. Neuro-transmitter diffuses across the synaptic cleft and binds to receptors

5. Sodium ions enter the post-synaptic neuron and cause depolarization

6. Nerve impulse setting off along the post-synaptic neuron

# Nerve impulses

## RESTING POTENTIALS

*The resting potential is the electrical potential across the plasma membrane of a cell that is not conducting an impulse.* Neurons pump ions across their plasma membranes by active transport. Sodium is pumped out of the neuron and potassium is pumped in. Concentration gradients of both sodium and potassium are established across the membrane. The inside of the neuron develops a net negative charge, compared with the outside, because of the presence of chloride and other negatively charged ions. There is therefore an electrical potential or voltage across the membrane. This is called the **resting potential**.

## ACTION POTENTIALS

*An action potential is the reversal and restoration of the electrical potential across the plasma membrane of a cell, as an electrical impulse passes along it (depolarization and repolarization).*

When an impulse passes along the neuron, sodium and potassium ions are allowed to diffuse across the membrane, through voltage-gated ion channels. The electrical potential across the membrane is initially reversed but is then restored. This is called an **action potential**. The figure (right) shows the changes in membrane polarization that occur during an action potential. The way in which action potentials pass down nerve fibres is explained below.
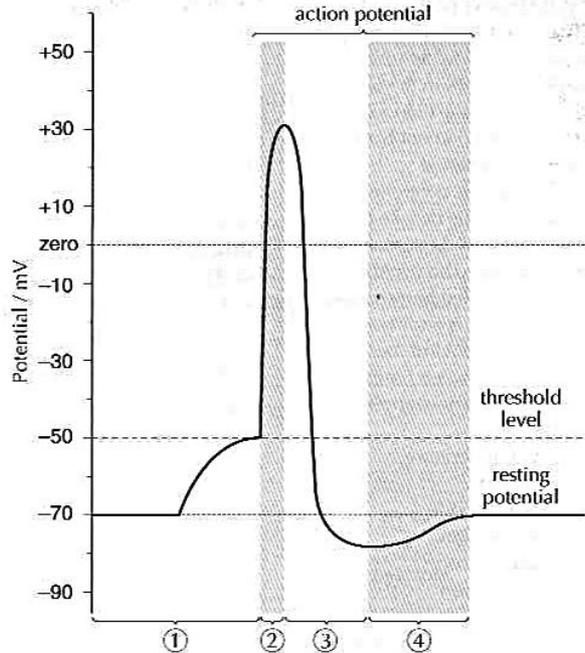


## STAGES IN THE PASSAGE OF A NERVE IMPULSE

(1) An action potential in one part of a neuron causes an action potential to develop in the next section of the neuron. This is due to diffusion of sodium ions between the region with an action potential and the region at the resting potential. These ion movements, local currents, reduce the resting potential. If the potential rises above the threshold level, voltage-gated channels open.

(2) Sodium channels open very quickly and sodium ions diffuse into the neuron down the concentration gradient. This reduces the membrane potential and causes more sodium channels to open. The entry of positively charged sodium ions causes the inside of the neuron to develop a net positive charge compared to the outside – the potential across the membrane is reversed. This is called **depolarization**.

(3) Potassium channels open after a short delay. Potassium ions diffuse out of the neuron down the concentration gradient through the opened channels. The exit of positively charged potassium ions cause the inside of the neuron to develop a net negative charge again compared with the outside – the potential across the membrane is restored. This is called **repolarization**.

(4) Concentration gradients of sodium and potassium across the membrane are restored by the active transport of sodium ions out of the neuron and potassium ions into the neuron. This restores the resting potential and the neuron is then ready to conduct another nerve impulse. As before, sodium ions diffuse along inside the neuron from an adjacent region that has already depolarized and initiate depolarization.
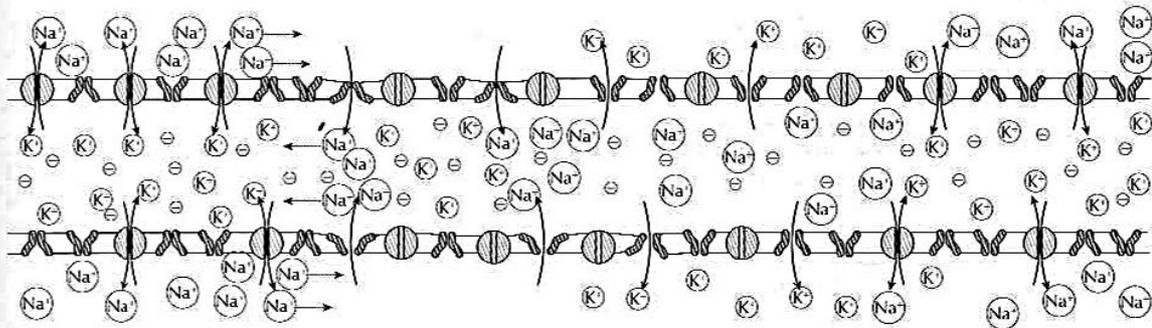


**Ion movements during an action potential**

# Maintaining the internal environment

## HOMEOSTASIS

Blood, and tissue fluid derived from blood, flow around or close to all cells in the body. Blood and tissue fluid form the internal environment of the body. This internal environment is controlled and varies very little despite large variations in the external environment. The control process is called **homeostasis**. *Homeostasis is maintaining the internal environment of the body between limits.* The parameters controlled include

- body temperature
- blood pH
- carbon dioxide concentration
- blood glucose concentration
- water balance

The nervous system and the endocrine system are both involved in controlling the internal environment. The endocrine system consists of glands, which release hormones that are transported in the blood.

## The endocrine and nervous systems

**Endocrine system**

- pituitary gland
- thyroid gland
- adrenal gland
- islets in the pancreas
- testes (ovaries in females)

**Nervous system**

- brain
- spinal cord
- peripheral nerves
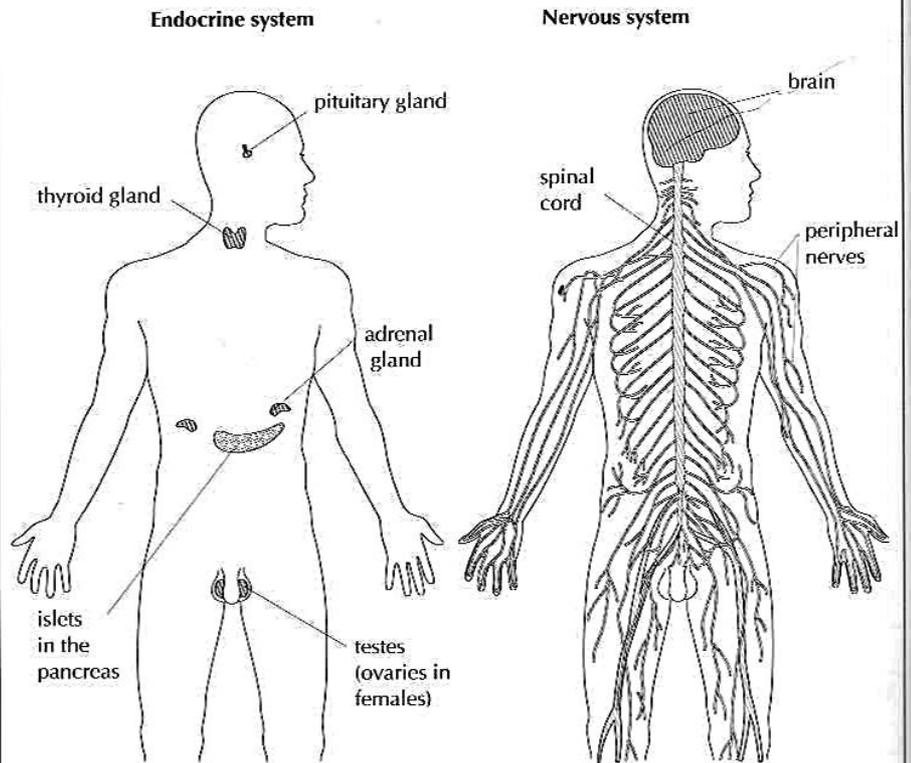
## CONTROLLING LEVELS BY NEGATIVE FEEDBACK

### 1. Feedback
In feedback systems, the level of a product feeds back to control the rate of its own production.

Level of product feeds back to affect the rate of production.

Processes that cause the production of something. → Product, e.g. heat or blood glucose.
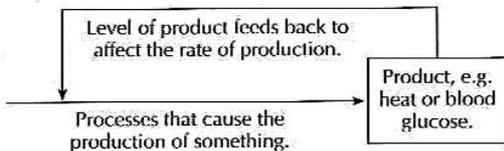
### 2. Negative feedback
Negative feedback has a stabilizing effect because a change in levels always causes the opposite change. A rise in levels feeds back to decrease production and reduce the level. A decrease in levels feeds back to increase production and raise the level. These are both negative feedback.

### 3. Monitoring levels

When the level falls significantly below the set point, it is increased by negative feedback.

Levels above set point — Set point — Levels below set point — TIME

Small fluctuations above and below the set point do not cause a response.

When the level rises significantly above the set point, it is reduced by negative feedback.
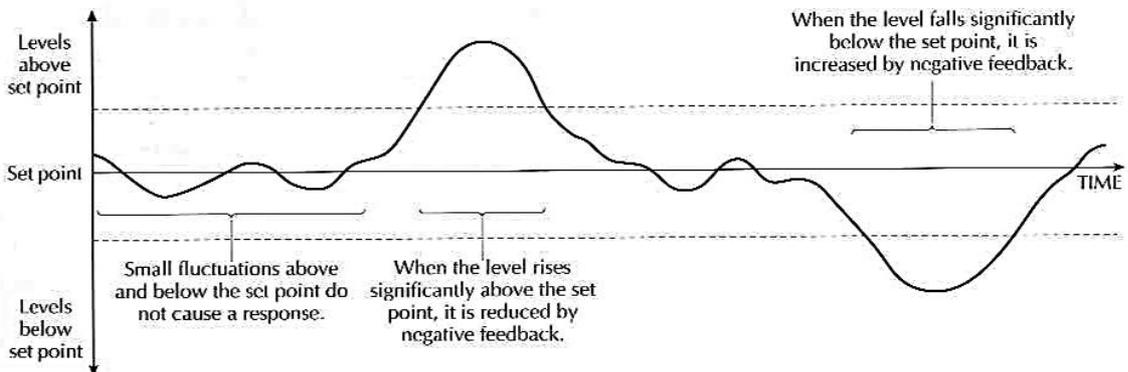
# Body temperature and blood glucose

## CONTROL OF BODY TEMPERATURE

The hypothalamus of the brain monitors the temperature of the blood and compares it with a set point, usually close to 37°C. If the blood temperature is lower or higher than the set point the hypothalamus sends messages to parts of the body to make them respond and bring the temperature back to the set point – negative feedback. These messages are carried by neurons. The responses affect the rate at which heat is produced, the rate at which it is transferred between parts of the body in the blood, or the rate at which it is lost from the body.

| Responses to overheating | Responses to chilling |
|---|---|
| Skin arterioles become wider, so more blood flows through the skin. This blood transfers heat from the core of the body to the skin. The temperature of the skin rises, so more heat is lost from it to the environment. | Skin arterioles become narrower and they bring less blood to the skin. The blood capillaries in the skin do not move, but less blood flows through them. The temperature of the skin falls, so less heat is lost from it to the environment. |
| Skeletal muscles remain relaxed and resting so that they do not generate heat. | Skeletal muscles do many small rapid contractions to generate heat. This is called shivering. |
| Sweat glands secrete large amounts of sweat making the surface of the skin damp. Water evaporates from the damp skin and this has a cooling effect. | Sweat glands do not secrete sweat and the skin remains dry. |
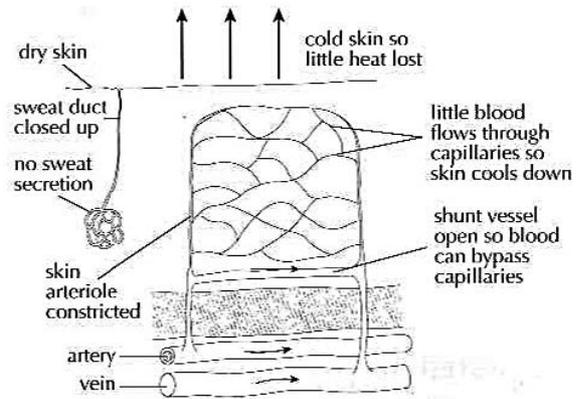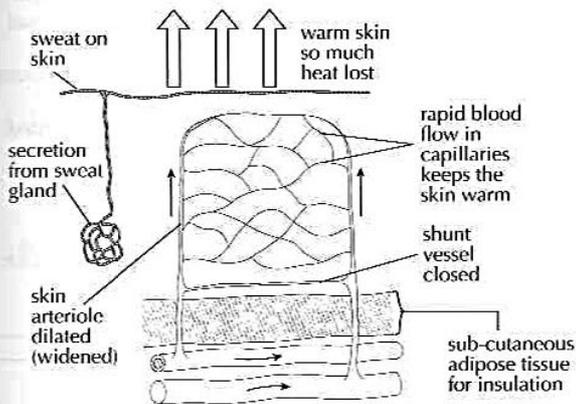


## CONTROL OF BLOOD GLUCOSE

Blood glucose concentration cannot be kept as steady as body temperature. Instead it is usually kept between 4 and 8 millimoles per $dm^3$ of blood. Cells in the pancreas monitor the concentration and send hormone messages to target organs when the level is low or high. Responses by the target organs affect the rate at which glucose is loaded into the blood or unloaded from it. The mechanisms involved are another example of negative feedback.

| Responses to high blood glucose levels | Responses to low blood glucose levels |
|---|---|
| β cells in the pancreatic islets produce insulin. | α cells in the pancreatic islets produce glucagon. |
| Insulin stimulates the liver and muscle cells to absorb glucose from the blood and convert it to glycogen. Granules of glycogen are stored in the cytoplasm of these cells. Other cells are stimulated to absorb glucose and use it in cell respiration instead of fat. These processes lower the blood glucose level. | Glucagon stimulates liver cells to break glycogen down into glucose and release the glucose into the blood. This raises the blood glucose level. |

## DIABETES

In some people the control of blood glucose does not work effectively and the concentration can rise or fall beyond the normal limits. The full name for this condition is **diabetes mellitus**. There are two forms of this condition, which are compared in the table below:

| Type I diabetes | Type II diabetes |
|---|---|
| The onset is usually during childhood. | The onset is usually after childhood. |
| β cells produce insufficient insulin. | Target cells become insensitive to insulin. |
| Insulin injections are used to control glucose levels. | Insulin injections are not usually needed. |
| Diet cannot by itself control the condition. | Low carbohydrate diets usually control the condition. |

# Reproductive systems

## THE FEMALE REPRODUCTIVE SYSTEM
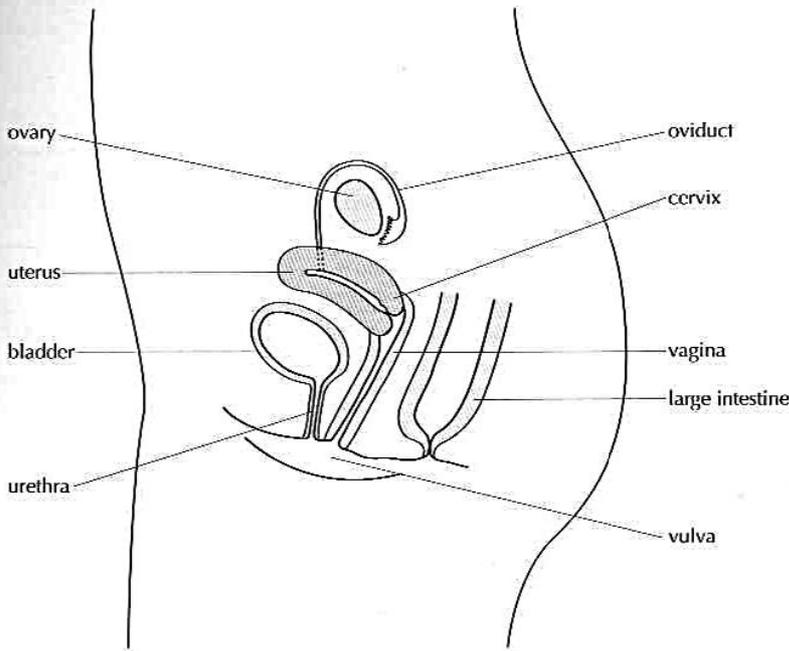
ovary

oviduct

cervix

uterus

bladder

vagina

large intestine

urethra

vulva

### TESTOSTERONE

Cells in the testes of males produce testosterone – the male sex hormone. Testosterone has several roles.
- The developing testes of a male fetus secrete testosterone, which causes male genitalia, including a penis, to develop in the fetus
- Levels of testosterone rise during puberty and cause male secondary sexual characteristics to develop – pubic hair, an enlarged penis and growth of skeletal muscles for example
- During adulthood, testosterone maintains the sex drive, the instinct which encourages men to have sexual intercourse and therefore pass on their genes to offspring.

Testosterone is also one of the hormones needed to stimulate sperm production by the testes.

## THE MALE REPRODUCTIVE SYSTEM

bladder

seminal vesicle

sperm duct

erectile tissue

prostate gland

penis

urethra

epididymis

foreskin

scrotum

testis
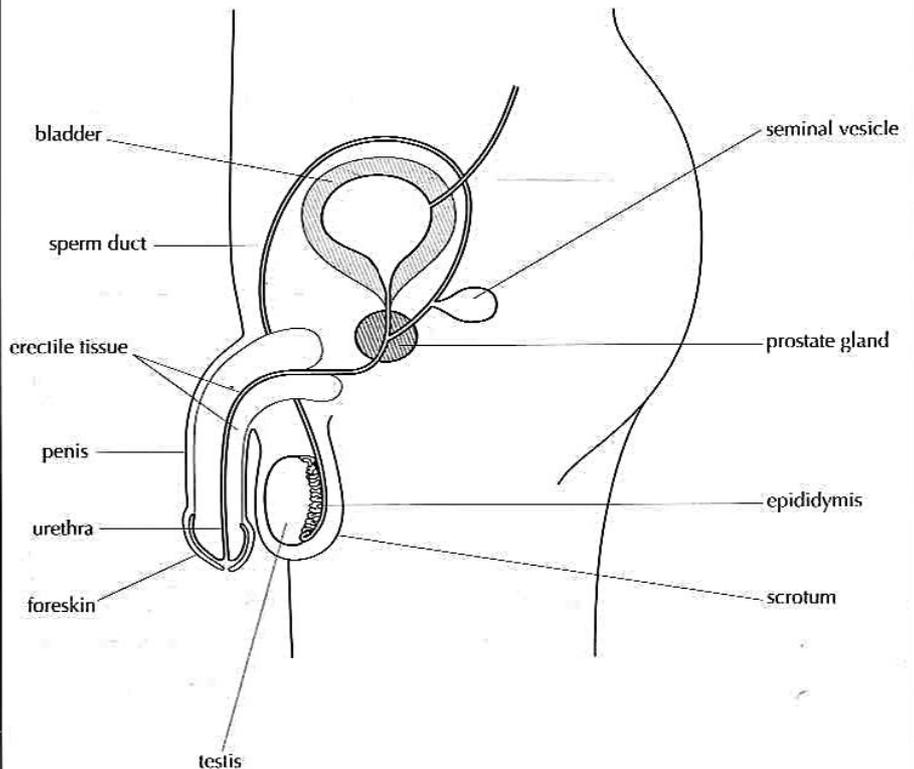
# The menstrual cycle

Between puberty and the menopause, women who are not pregnant follow a cycle called the menstrual cycle. This cycle is controlled by hormones FSH and LH produced by the pituitary gland and estrogen and progesterone produced by the ovary. The figure below shows the levels of these hormones during the menstrual cycle. It also shows the changes in the ovary and in the uterus.

① FSH level rises and stimulates follicle development and estrogen secretion by cells of the follicle.

⑤ LH rises to a peak and causes the egg to be released from the follicle - ovulation.

⑥ LH causes the follicle cells to secrete less estrogen (negative feedback) and more progesterone. After ovalution LH causes the follicle to develop into the corpus luteum.

⑧ High progesterone and estrogen levels inhibit FSH and LH secretion. This is negative feedback because FSH and LH stimulated estrogen and progesterone secretion.

⑩ FSH levels rise again, starting the next menstrual cycle.

**FSH and LH levels**

FSH

LH

**ovary development**

follicle starting to develop

follicle nearly mature

corpus luteum

**estrogen and progesterone levels**

estrogen

progesterone

② Estrogen makes the follicle cells produce more FSH receptors and so respond more strongly to FSH.

③ This positive feedback makes estrogen levels rise and stimulate the repair of the uterus lining.

④ Estrogen levels rise to a peak and stimulate LH secretion by the pituitary gland.

⑦ The corpus luteum secretes large amounts of progesterone, which causes the uterus lining to prepare for an embryo.

⑨ Progesterone and estrogen levels fall if no embryo has been formed. Eventually the levels are low enough to allow FSH and LH secretion.

**uterus wall development (endometrium)**

MENSTRUATION | OVULATION | MENSTRUATION

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34

DAYS AFTER THE START OF MENSTRUATION

# In vitro fertilization

## INFERTILITY

Some couples do not achieve fertilization and pregnancy when they wish to, despite sexual intercourse during the period in the middle of the menstrual cycle when ovulation usually occurs. This is called infertility. It may be temporary, because the causes can be resolved, or permanent.

Approximately one in six couples have some experience of temporary or permanent infertility. Many of these couples can be helped to have a child by *in vitro* fertilization – IVF. For example, blocked oviducts in a woman prevent conception, but IVF can overcome this problem. Other problems cannot be resolved by IVF, for example low or zero sperm counts in men.

The process of IVF is outlined (right).

## Timetable for IVF

Weeks of the treatment cycle

week 1
week 2
week 3
week 4 — 21.00
week 5 — 9.00 10.00 14.00
week 6 — 8.00
week 7 — 14.00
week 8
week 9

① A drug is injected once a day for three weeks, to stop the woman's normal menstrual cycle.

② Large doses of FSH are injected once a day or 10–12 days to stimulate the ovaries to develop many follicles.

③ HCG (another hormone) is injected 36 hours before egg collection, to loosen the egg in the follicles and to make them mature.

④ The man provides semen by ejaculating into a jar. The sperm are processed to concentrate the healthiest ones.

⑤ The eggs are extracted from the follicles using a device inserted through the wall of the vagina.

⑥ Each egg is mixed with sperm in a shallow dish. The dishes are kept overnight in an incubator.

⑦ The dishes are checked to see if fertilization has worked.

⑧ Two or three embryos are selected and placed, via a long plastic tube, into the uterus.

⑨ A pregnancy test is done to see if any embryos have implanted.

⑩ A scan is done to see if the pregnancy is continuing normally. The heart should be visible beating.

## ETHICAL ISSUES ASSOCIATED WITH IVF

Some issues are controversial and around the world the views held by people may vary considerably. Ethical issues involve questioning whether something is wrong or right. Decisions cannot be made using scientific methods, but scientists have an obligation to consider ethical issues.

### Ethical arguments against IVF

- Inherited forms of infertility might be passed on to children, which means that the suffering of the parents is repeated in their offspring.
- More embryos are often produced than are needed and the spare embryos are sometimes killed, denying them the chance of life.
- Embryologists select embryos to transfer to the uterus, so humans are deciding whether new individuals survive or die.
- IVF is an unnatural process, carried out in laboratories, in contrast to natural conception occurring as a result of an act of love.
- Infertility should be accepted as the will of God and it is wrong to try to circumvent it by using IVF to have a child.

### Ethical arguments for IVF

- Many forms of infertility are due to environmental factors, so offspring will not inherit them.
- Any embryos that are killed during IVF are unable to feel pain or suffer, because their nervous system has not developed.
- Suffering due to genetic disease could be reduced if embryos were screened before being transferred to the uterus.
- Parents willing to go through the process of IVF must have a strong desire for children and so are likely to be loving parents.
- Infertility brings great unhappiness to parents who want to have children, which in some cases can be overcome by IVF.

1   Respiration in humans and other mammals generates heat which can be used to keep the body temperature above that of the surroundings.

Many mammals found in the southern hemisphere, including marsupials, vary their body temperature according to a daily cycle. The mouse lemur (*Microcebus myoxinus*) is an example of such a mammal. To investigate this daily cycle, *M. myoxinus* was studied in its native habitat in Madagascar. Data-loggers which recorded body temperature ($T_b$) over 24-hour periods were implanted in the bodies of several of these mammals. Air temperature ($T_a$) was recorded at the same time. A typical set of results is shown in the graph below.
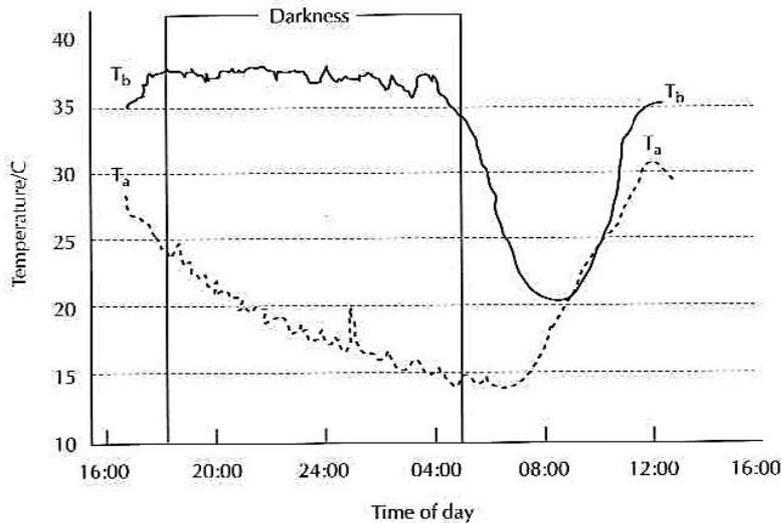


[Source: Cossins and Barnes, Nature (1996), 384, page 582]

a) Using only the data in the graph, state two differences between $T_a$ and $T_b$ during the hours of darkness.                    [2]

b) $T_b$ rises from 08:00 to 12:00. Explain briefly how this temperature rise occurs.                    [2]

c) Predict, with a reason, whether *M. myoxinus* is active in the hours of daylight or the hours of darkness.                    [1]

2   a) (i) State the function of phagocytic leukocytes.                    [1]

   (ii) Outline where in the body phagocytic leukocytes carry out their function.                    [2]

   b) Explain briefly the need for small numbers of many types of B-lymphocyte in the body.                    [2]

3   The diagram right shows part of the human gas exchange system.

   a) State the name of the parts labelled I and II.                    [2]

   b) I and II allow the lungs to be ventilated. Explain briefly the need for ventilation.                    [2]

   c) Draw and label a diagram of alveoli.                    [3]
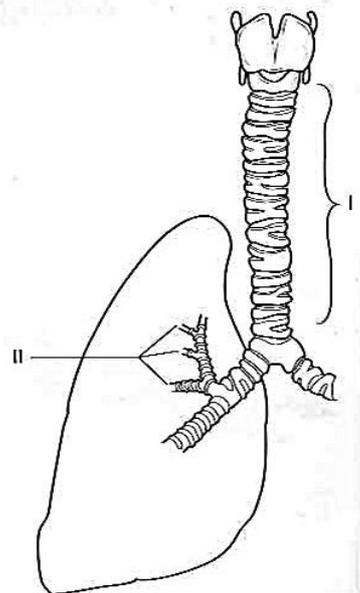
# DNA structure and replication

## DNA STRUCTURE

At one end of each strand is a phosphate linked to carbon atom 5 of deoxyribose. This is the 5' terminal.

Hydrogen bonds (shown as ▬) link the bases. Two bonds form between adenine and thymine and three bonds between guanine and cytosine. Only these pairs can form hydrogen bonds.

Two of the bases in DNA are purines: adenine and guanine. They have two rings in their molecules. Two of the bases in DNA are pyrimidines. Cytosine and thymine are pyrimidines. They have one ring in their molecule. Only a purine plus a pyrimidine will fit in the space between the sugar–phosphate backbones.

Adjacent nucleotides are linked by a bond between the phosphate group of one nucleotide and carbon atom 3 of the other nucleotide.

adenine    thymine

guanine    cytosine

At one end of each strand is a hydroxyl group attached to carbon atom 3 of deoxyribose. This is therefore the 3' terminal.

The two strands have their 3' and 5' terminals at opposite ends – they are anti-parallel. DNA replication can only occur in a 5'→3' direction so a different method is needed for the two strands.

## DNA REPLICATION

① The cell produces many free nucleotides for DNA replication. Each has three phosphate groups – they are deoxyribonucleoside triphosphates. Two phosphates are removed during replication to release energy.

② Helicase uncoils the DNA double helix and splits it into two template strands.

③ DNA polymerase III adds nucleotides in a 5'→3' direction. On one strand it moves in the same direction as the replication fork, close to helicase. On the other template strand it moves in the opposite direction.

Primer

⑥ Short lengths of DNA are formed between RNA primers on this strand, called Okazaki fragments.

⑧ DNA ligase seals up the nick by making another sugar-phosphate bond.

Helicase

⑦ DNA polymerase I removes the RNA primer and replaces it with DNA. A nick is left where two nucleotides are still unconnected.

⑤ DNA polymerase III starts replication next to the RNA primer and adds nucleotides in a 5'→3' direction. It therefore moves away from the replication fork on this strand.

④ RNA primase adds a short length of RNA attached by base pairing to the template strand of DNA. This acts as a primer, allowing DNA polymerase to bind and begin replication.
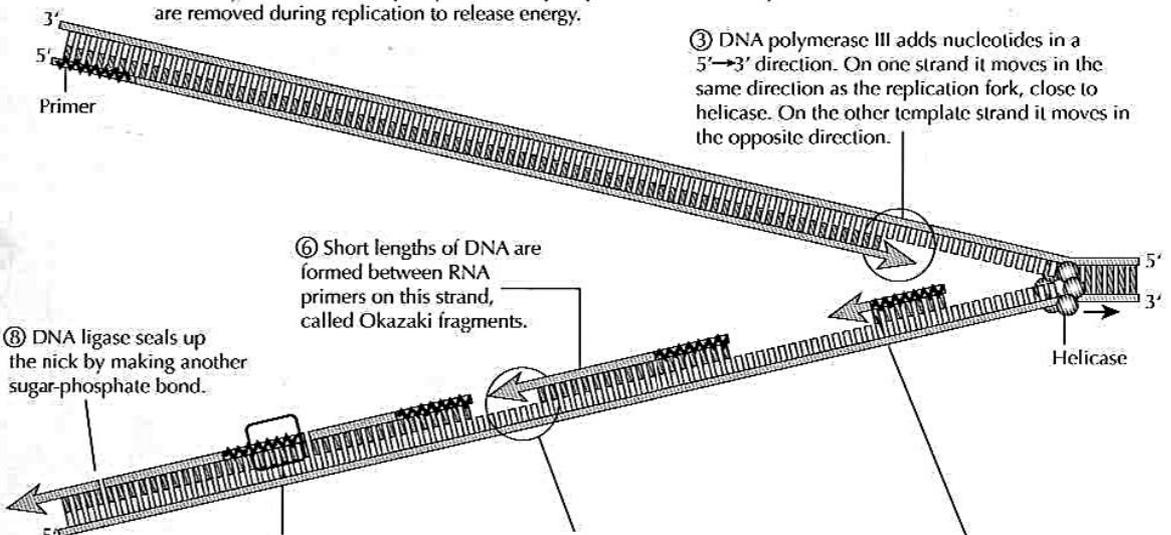
# Organization of DNA in eukaryotes

## DNA IN PROKARYOTES AND EUKARYOTES

All eukaryotes and prokaryotes use DNA as their genetic material and use the same genetic code, but there are differences in the way that the DNA is organized and used. Prokaryotes have naked DNA, which consists mostly of single copy genes that are transcribed and translated without modification. The situation in eukaryotes is more complex:

### Replication initiation sites

Replication of DNA begins at special initiation points. Eukaryotes have many of these initiation points along each chromosome. Most prokaryotes have only one point on their DNA molecule where replication is initiated.

### Nucleosomes

In eukaryotes, the DNA is associated with proteins to form nucleosomes – globular structures that contain eight histone proteins, with DNA wrapped around. Another histone protein bonds the structure together (above right). In an interphase nucleus in eukaryotes the DNA resembles a string of beads (right). Nucleosomes have two functions:
- they help to package up the DNA during mitosis and meiosis by the process of supercoiling
- they can be used to mark particular genes, either to promote gene expression by transcription and translation, or to cause silencing of a gene by preventing transcription.

### Repetitive sequences

Much of the DNA in eukaryotes consists of repetitive base sequences, which are not translated. Highly repetitive sequences, sometimes called satellite DNA, are sequences of between 5 and 300 bases, that may be repeated as many as 10 000 times. These constitute 5–45% of typical eukaryote DNA. Its function is not yet clear.
A surprisingly small proportion of eukaryotic DNA is single copy, or unique genes.

### Introns and exons

Many genes in eukaryotes contain **introns** – sequences of bases that are transcribed, but not translated. **Exons** are sequences of bases that are transcribed and translated. A typical eukaryote gene consists of a series of exons and introns. After transcription of the whole gene, the introns are removed to form mature mRNA, in a process called post-transcriptional modification (below right). Prokaryotes do not usually have introns in their genes.

percentage of genes

*Saccharomyces cerevisiae* (a yeast)

*Drosophila melanogaster* (fruit fly)

mammals

number of exons

## Nucleosome structure



nucleosome core consisting of eight histone protein molecules

DNA linker

another histone protein holding the nucleosome together

DNA wrapped twice around the nucleosome core

DNA linker continuing towards the next nucleosome

DNA strand

nucleosomes

nucleosomes can be tagged with proteins to promote or repress transcription

DNA

transcription

introns

mRNA

post-transcriptional modification

exon

mature mRNA

translation

protein

# Transcription of DNA

## RNA POLYMERASE AND TRANSCRIPTION

DNA is split into two strands by RNA polymerase. One of these strands forms the template for transcription. The base sequence of the mRNA is complementary to it. The other strand has the same base sequence as the mRNA (except for T instead of U) and is therefore called the **sense strand**. The strand that forms the template and is transcribed is called the **antisense strand**.



DNA is unwound by the front of RNA polymerase

DNA is rewound into a double helix by the rear of RNA polymerase

Part of the DNA of a gene

5'
3'

3'
5'

GTACCGTTAG
GUACCGUUAG
CATGGCAATC

sense strand

antisense strand

RNA polymerase

mRNA molecule produced by RNA polymerase

5'

Free nucleoside triphosphates are used by RNA polymerase to extend the growing mRNA molecule. Two phosphates are removed as they are linked on, converting them into RNA nucleotides. The 5' end of the nucleotide is added to the 3' end of the growing chain – transcription thus moves in a 5'→ 3' direction.

## TRANSLATING THE GENETIC CODE

Messenger RNA carries the information needed for making polypeptides out from the nucleus to the cytoplasm of eukaryotic cells. The information is in a coded form, which is decoded during translation. The base sequence of mRNA is translated into the amino acid sequence of a polypeptide. Key features of the code are described (below left). The meaning of each codon is shown in the table (below right).

The genetic code is a **triplet code** – three bases code for one amino acid. A group of three bases is called a **codon**. There are 64 different codons ($4^3$). This gives more than enough codons to code for the twenty amino acids in proteins. If codons consisted of two bases there would be sixteen ($4^2$) – not enough. None of the 64 codons are unused. Instead, the genetic code is **degenerate**. This means that it is possible for two or more codons to code for the same amino acid. The genetic code is **universal**. With just a few minor exceptions, living organisms use precisely the same code. Viruses also use this code.

| First base of codon (5' end) | Second base of codon on messenger RNA | | | | Third base of codon (3' end) |
|---|---|---|---|---|---|
| | U | C | A | G | |
| U | Phenylalanine | Serine | Tyrosine | Cysteine | U |
| | Phenylalanine | Serine | Tyrosine | Cysteine | C |
| | Leucine | Serine | STOP | STOP | A |
| | Leucine | Serine | STOP | Tryptophan | G |
| C | Leucine | Proline | Histidine | Arginine | U |
| | Leucine | Proline | Histidine | Arginine | C |
| | Leucine | Proline | Glutamine | Arginine | A |
| | Leucine | Proline | Glutamine | Arginine | G |
| A | Isoleucine | Threonine | Asparagine | Serine | U |
| | Isoleucine | Threonine | Asparagine | Serine | C |
| | Isoleucine | Threonine | Lysine | Arginine | A |
| | Methionine / START | Threonine | Lysine | Arginine | G |
| G | Valine | Alanine | Aspartic acid | Glycine | U |
| | Valine | Alanine | Aspartic acid | Glycine | C |
| | Valine | Alanine | Glutamic acid | Glycine | A |
| | Valine | Alanine | Glutamic acid | Glycine | G |

# Ribosomes and transfer RNA

## tRNA AND tRNA ACTIVATING ENZYMES

There are many different types of tRNA in a cell, which have an important role in translation.

All tRNA molecules have:
- sections that become double stranded by base pairing, creating loops (above right)
- a triplet of bases called the anticodon, in a loop of seven bases
- two other loops
- the base sequence CCA at the 3′ terminal, which forms a site for attaching an amino acid.

These features allow all tRNA molecules to bind to three sites on the ribosome.

The base sequence of tRNA molecules varies and this causes some variable features in its structure:
- an extra small loop is sometimes present
- the base paired sections are sometimes helical.

The variable features give each type of tRNA a distinctive three-dimensional shape and distinctive chemical properties (below right). This allows the correct amino acid to be attached to the 3′ terminal by an enzyme called a **tRNA activating enzyme**. There are twenty different tRNA activating enzymes – one for each of the twenty different amino acids. Each of these enzymes attaches one particular amino acid to all of the tRNA molecules that have an anticodon corresponding to that amino acid. The tRNA activating enzymes recognize these tRNA molecules by their shape and chemical properties.

Energy from ATP is needed for the attachment of amino acids. A high-energy bond is created between the amino acid and the tRNA. Energy from this bond is later used to link the amino acid to the growing polypeptide chain during translation.

### tRNA structure
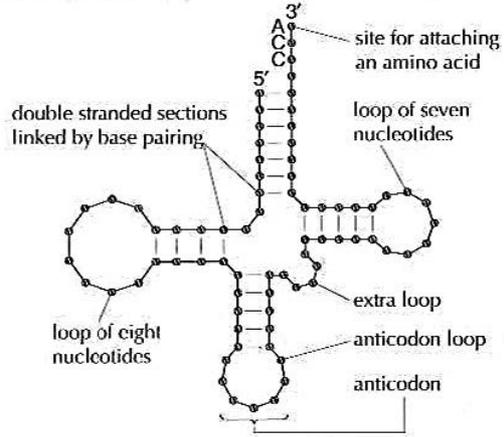


### Three-dimensional view of tRNA
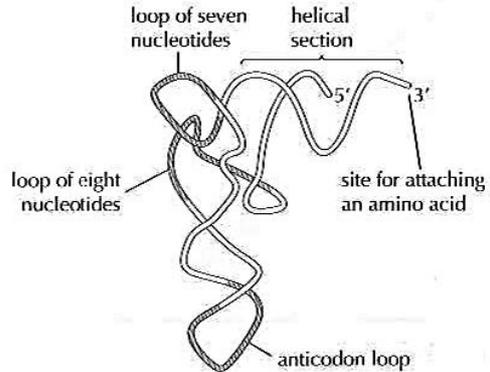


## STRUCTURE AND FUNCTION OF RIBOSOMES

Ribosomes have a complex structure, with these features.
- Proteins and ribosomal RNA molecules (rRNA) both form part of the structure.
- There are two subunits, one large and one small.
- There are three binding sites for tRNA on the surface of the ribosome. Two tRNA molecules can bind at the same time to the ribosome.
- There is a binding site for mRNA on the surface of the ribosome.

The structure of a ribosome is shown in outline in the figure (right), with the three tRNA binding sites.

Ribosomes in the cytoplasm are called **free ribosomes**. They synthesize proteins for use within the cell. Ribosomes can also be attached to membranes of the endoplasmic reticulum. They are called **bound ribosomes** and synthesize proteins for secretion from the cell or for lysosomes.
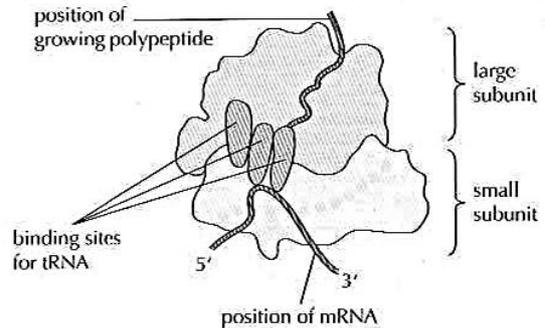


## PEPTIDE BONDS

Ribosomes are the site of polypeptide synthesis. This involves linking amino acids together by a condensation reaction (shown on page 15). The linkage between the amino acids is a peptide bond. Perhaps unexpectedly, it is rRNA and not proteins in the ribosome that catalyse the reaction in which the peptide bond is formed. The diagram (right) shows a peptide bond between two amino acids.
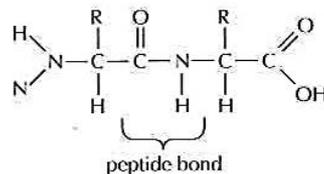
# Polysomes and polypeptide elongation

The figure (right) is an electron micrograph showing groups of ribosomes called **polysomes** (or polyribosomes). A polysome is a group of ribosomes moving along the same mRNA, as they simultaneously translate it. Each ribosome follows a series of steps that is repeated many times to translate the mRNA. One amino acid is added to the elongating polypeptide each time the cycle of steps is repeated (see below). As ribosomes move along the mRNA towards the 3' end, the polypeptide is gradually elongated.
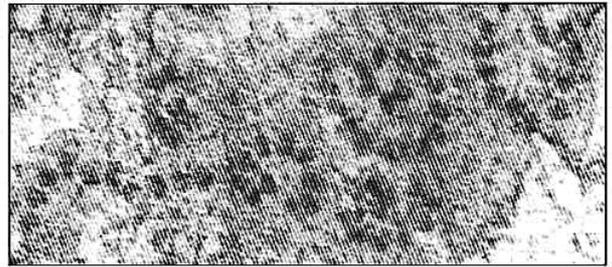
(× 180 000)

## POLYPEPTIDE ELONGATION

① One of the binding sites for tRNA is vacant. The small subunit of the ribosome ensures that only a tRNA with the anticodon that is complementary to the next codon binds to it.
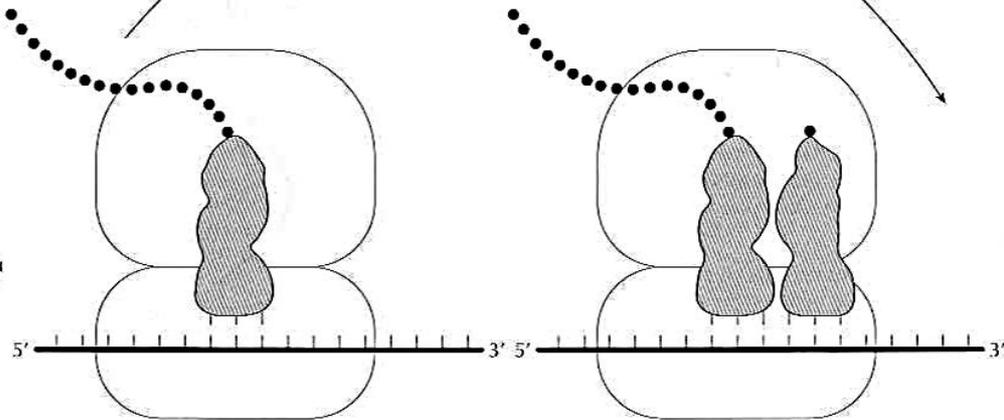
④ The tRNA shown on the left has been displaced to the third binding site, and detaches from the ribosome. It can be used again in translation after a tRNA activating enzyme has added another amino acid to it.

② The large subunit of the ribosome advances over the small subunit and detaches the polypeptide from the tRNA shown on the left. The polypeptide is attached by a peptide linkage to the single amino acid held by the tRNA shown on the right.
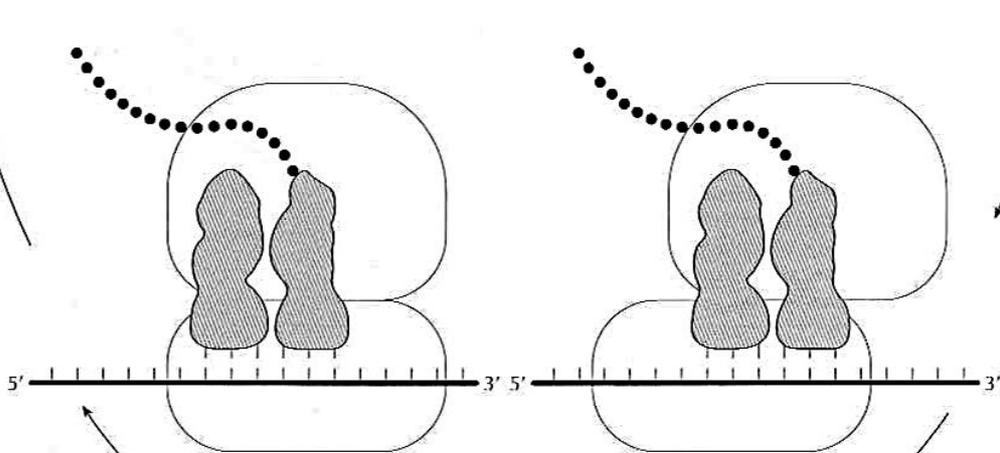
③ The small subunit slides across the large subunit. At the same time it moves three nucleotides on along the mRNA in a 5' to 3' direction. Translation always occurs in a 5' to 3' direction along mRNA.

# Starting and stopping translation

Special steps are needed to start the process of translation and to stop it. These steps are called **initiation** and **termination**. The three stages of translation are thus initiation, elongation and termination.

## INITIATION OF TRANSLATION

(a) tRNA with the anticodon complementary to the start codon binds to the small subunit of the ribosome

(b) The small subunit, carrying the tRNA binds to the 5' end of the messenger RNA

5' end → 3' end AUG

(c) The small subunit slides along the mRNA until it reaches the start codon, which shows where translation should be started

5' end → 3' end AUG

(d) The large subunit of the ribosome binds to the small subunit

5' end → 3' end AUG

(e) Another tRNA, with the anticodon complementary to the next codon on the mRNA, binds to the ribosome. Elongation of a polypeptide can now start

5' end → 3' end AUG

## TERMINATION OF TRANSLATION

(w) The ribosome moves along the mRNA in a 5'→3' direction, translating each codon into an amino acid on the elongating polypeptide

from 5' end → 3' end UGA

(x) The ribosome reaches a stop codon. No tRNA molecule has the complementary anticodon

from 5' end → 3' end UGA

(y) The released polypeptide has usually already started folding up to form the protein's final shape

The large subunit advances over the small subunit. The polypeptide is released from the tRNA

from 5' end → 3' end UGA

(z) The tRNA detaches and the large subunit, small subunit and mRNA all separate

from 5' end → 3' end UGA

Proteins synthesized by free ribosomes mostly remain and are used in the cytoplasm. Proteins synthesized by ribosomes bound to the ER are mostly secreted from the cell or are used in lysosomes

# Intramolecular bonding in proteins

Polypeptides have a main chain consisting of a repeating sequence of covalently bonded carbon and nitrogen atoms: N – C – C – N – C – C, and so on. Each nitrogen atom has a hydrogen atom bonded to it ( N – H ). Every second carbon atom has an oxygen atom bonded to it ( C = O ).

$$N-C-C-N-C-C$$
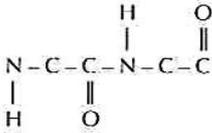
Hydrogen bonds can form between N – H and C = O groups, if they are brought close together. For example, if sections of polypeptide run parallel, hydrogen bonds can form between them. The structure that develops is called a ß-pleated sheet. If the polypeptide is wound into a right-handed helix, hydrogen bonds can form between adjacent turns of the helix. The structure that develops is called an α-helix. Because the groups forming hydrogen bonds are regularly spaced, secondary structures always have the same dimensions.

In addition to the hydrogen bonding in ß-pleated sheets and α-helices, there are many other types of bonding. Most of these involve the R groups of the amino acids. The figure (below) shows some of these bonds.
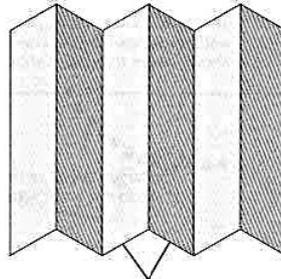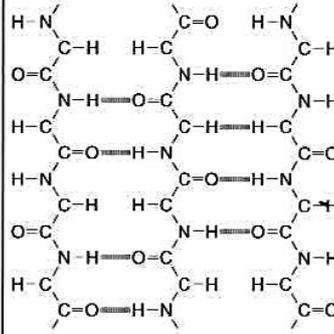
## β-PLEATED SHEET

Bond angles give the sheet a pleated shape

## α -HELIX
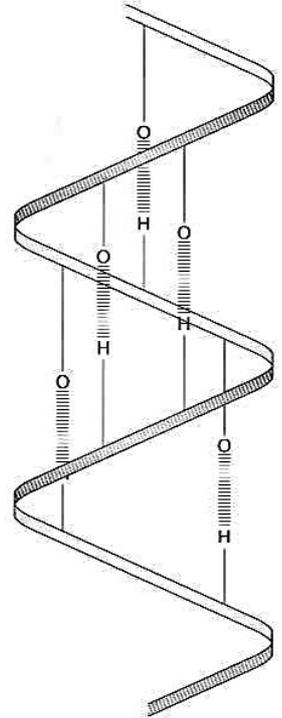
## Types of intramolecular bond in proteins

Ionic bonds can form between positively and negatively charged R groups

Acidic amino acids have R groups that can lose an H⁺ ion and so become negatively charged

Basic amino acids have R groups that can accept an H⁺ ion and so become positively charged

Disulfide bridges, which are strong covalent bonds can form between pairs of cysteines

Hydrophobic interactions, which are weak bonds, can form between R groups that are non-polar including all those projecting inwards here

Hydrogen bonds can form between some R groups
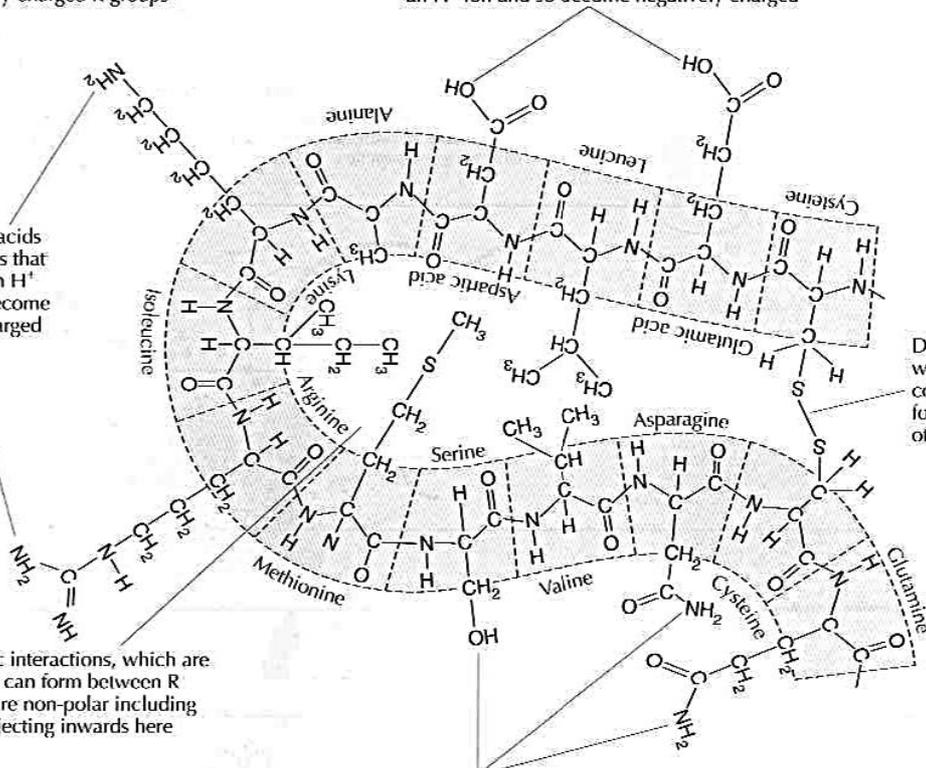
# Protein structure

Proteins have a complex structure, which can be explained by defining four levels of structure, primary, secondary, tertiary and quaternary structure.

## PRIMARY STRUCTURE

*Primary structure is the number and sequence of amino acids in a polypeptide.* Most polypeptides consist of between 50 and 1000 amino acids. The primary structure is determined by the base sequence of the gene that codes for the polypeptide. The figure (below) shows the primary structure of ß-endorphin, a protein consisting of a single polypeptide of 31 amino acids that acts as a neurotransmitter in the brain.

**Primary structure of ß-endorphin**

Alanine → Isoleucine → Isoleucine → Lysine

Asparagine → Alanine → Histidine → Lysine

Lysine → Glycine → Glutamine → Tyrosine

Glycine → Glycine → Phenylalanine → Methionine

Threonine → Serine → Glutamic acid → Lysine

Serine → Glutamine → Threonine → Proline

Leucine → Valine → Threonine → Leucine

Phenylalanine → Lysine → Asparagine
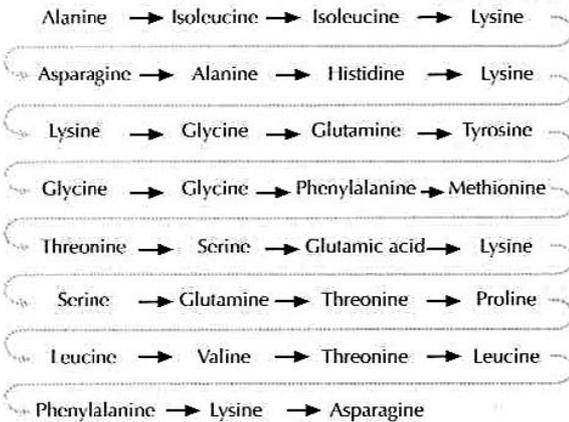
## SECONDARY STRUCTURE

*Secondary structures are regular repeating structures, including ß-pleated sheets and α-helices stabilized by hydrogen bonds between groups in the main chain of the polypeptide.* In many proteins, parts of the polypeptide form secondary structures and other parts do not. In some proteins secondary structures do not form at all. In a few proteins almost all of the polypeptide forms secondary structures. For example almost all of myosin molecules is α-helix and almost all of fibroin (silk protein) is β-pleated sheet. The figure (below) shows the position of secondary structures in lysozyme, using the ribbon model. Sections of α-helix are represented by helical ribbons and sections of β-pleated sheet are represented by arrows.

**Ribbon model of lysozyme**
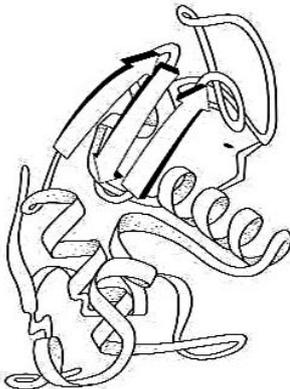


## TERTIARY STRUCTURE

*Tertiary structure is the three-dimensional conformation of a polypeptide.* It is formed when the polypeptide folds up after being produced by translation. The conformation is stabilized by intramolecular bonds that form between amino acids in the polypeptide, especially between their R groups. These include ionic bonds, hydrogen bonds, hydrophobic interactions and disulfide bridges. The intramolecular bonds are often formed between amino acids that are widely separated in the primary structure of the polypeptide, but which are brought together during the folding process. The figure below shows the tertiary structure of lysozyme using the sausage model.

**Sausage model of lysozyme**
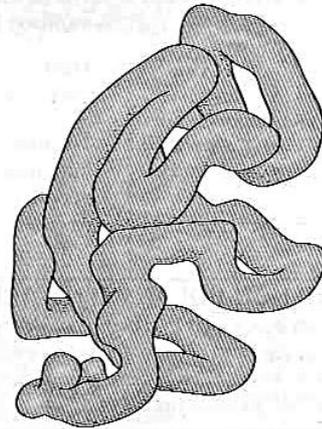


## QUATERNARY STRUCTURE

*Quaternary structure is the linking together of two or more polypeptides to form a single protein.* For example, insulin consists of two polypeptides linked together, collagen consists of three polypeptides and hemoglobin consists of four. In some cases proteins also contain a non-polypeptide structure called a **prosthetic group**. Each of the four polypeptides in hemoglobin is linked to a heme group, which is not made of amino acids. Proteins with a prosthetic group are called **conjugated proteins**. The figure (below) shows the quaternary structure of hemoglobin.

**Sausage model of hemoglobin**



alpha chain · alpha chain · beta chain · heme group · beta chain
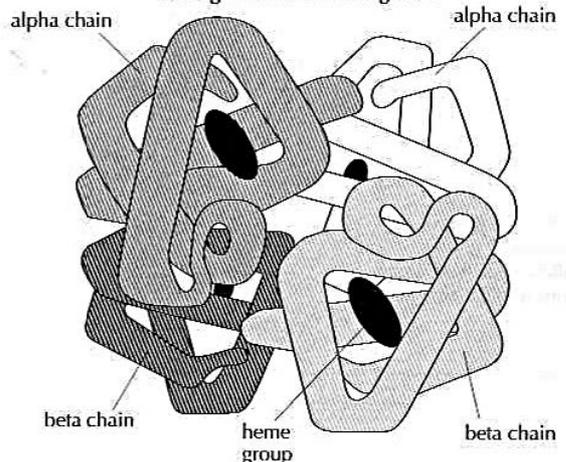
# Protein functions

## FUNCTIONS OF FIBROUS AND GLOBULAR PROTEINS

Proteins can be divided into two types according to their shape – **fibrous** or **globular**. Fibrous proteins have a long and narrow shape. They are mostly insoluble in water. Globular proteins have a rounded shape. They are mostly soluble in water. Two examples of both fibrous and globular proteins are given in the table (below).

Proteins have a huge range of functions in living organisms. Some proteins are located in membranes – their functions are listed on page 8. Four of the functions of non-membrane proteins are listed in the table (below). Proteins can also be used as food stores, for example casein in milk, as pigments, for example opsin in the retina, as toxins as in some snake venom, as hormones, for example insulin, and as enzymes.

| Function | Example | Details | Shape |
|---|---|---|---|
| Structural | Collagen | The function of collagen is to strengthen bone, tendon and skin. These tissues all produce tough collagen fibres in the spaces between their cells | Fibrous |
| Transport | Hemoglobin | The function of hemoglobin is to bind oxygen in the lungs and to transport it to respiring tissues | Globular |
| Movement | Myosin | The function of myosin (with another protein called actin) is to cause contraction in muscle fibres and as a result cause movement in animals | Fibrous |
| Defence | Immunoglobulin | The function of immunoglobulin is to act as antibodies. Part of the immunoglobulin molecule can be varied, so that an almost endless variety of different antibodies can be produced | Globular |

## POLAR AND NON-POLAR AMINO ACIDS IN PROTEINS

Amino acids can be divided into two types according to the chemical characteristics of their R group. Polar amino acids have hydrophilic R groups and non-polar amino acids have hydrophobic R groups. The distribution of polar and non-polar amino acids in a protein molecule influence where the protein is located in a cell and what function it can carry out. The figures (below) show examples of this.

**Positions of proteins in and out of membranes**

Non-polar amino acids in the centre of water-soluble proteins stabilize their structure.

Polar amino acids on the surface of proteins make them water soluble.

Non-polar amino acids cause proteins to remain embedded in membranes.

Polar amino acids create channels through which hydrophilic substances can diffuse. Positively charged R groups allow negatively charged ions through and vice versa.

Polar amino acids cause parts of membrane proteins to protrude from the membrane. Transmembrane proteins have two such regions.

**Superoxide dismutase – an enzyme found in all aerobic organisms**

A ring of amino acids with negatively charged R-groups repel the negatively charged superoxide ions and help to direct them to the active site.

The active site is a cleft containing amino acids with positively charged R-groups which attract the negatively charged superoxide ions that are the substrate of the enzyme.
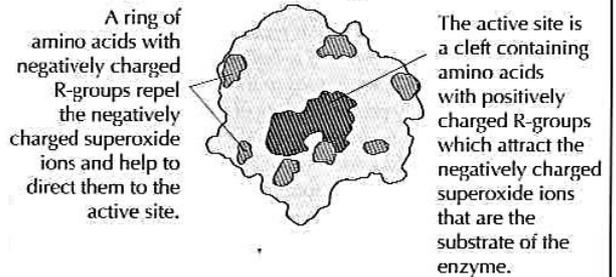
**Lipase – an enzyme that works in the small intestine**

Part of the enzyme molecule acts as a hinged lid which can cover the active site when not in use, hiding the non-polar R-groups.

polar region

The active site is a cleft containing amino acids with non-polar R-groups which bind non-polar triglycerides.

non-polar region

A protein cofactor binds to the enzyme, and helps lipase to bind to the surface of lipid droplets because it has non-polar R-groups on its surface.

# Enzymes and activation energy

## ENERGY CHANGES DURING CHEMICAL REACTIONS

During chemical reactions, reactants are converted into products. Before a molecule of the reactant can take part in the reaction, it has to gain some energy. This is called the **activation energy** of the reaction. The energy is needed to break bonds within the reactant. Later during the progress of the reaction, energy is given out as new bonds are made. Most biological reactions are exothermic – the energy released is greater than the activation energy.

Enzymes reduce the activation energy of the reactions that they catalyse and therefore make it easier for these reactions to occur. The graph (below) shows energy changes during uncatalysed and catalysed exothermic reactions.

The chemical environment provided by the active site for the substrate causes changes within the substrate molecule, which weakens its bonds. The substrate is changed into a transition state, which is different from the transition state during the reaction when an enzyme is not involved. The transition state achieved during binding to the active site has less energy and this is how enzymes are able to reduce the activation energy of reactions.

### Energy changes during a chemical reaction
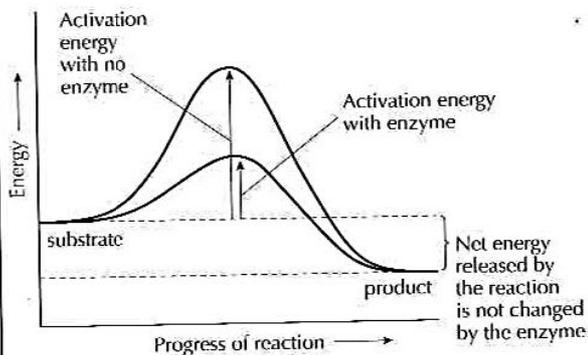


## THE INDUCED FIT MODEL

Biochemists have investigated many enzymes and found that the lock and key model does not fully explain the binding of the substrate to the active site. Until the substrate binds, the active site does not fit the substrate precisely. As the substrate approaches the active site and binds to it, the shape of the active site changes and only then does it fit the substrate. The substrate induces the active site to change, weakening bonds in the substrate during the process and thus reducing the activation energy. The figure (right) shows the induced fit model of enzyme activity.

Some enzymes can have quite broad specificity, for example some proteases. The induced fit model explains this better than the lock and key model – if the shape of an active site alters when substrates bind, several different but similar substrates could easily bind successfully to it.
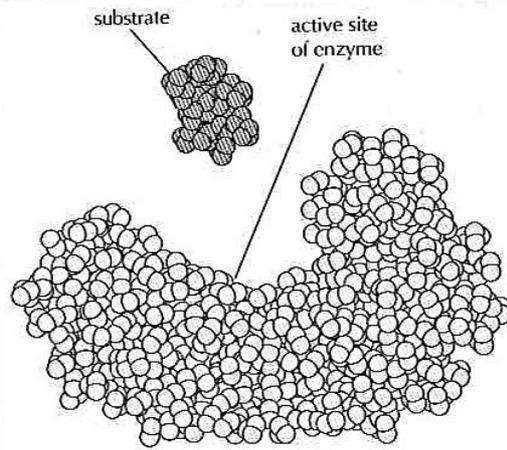


As the substrate binds, the conformation of the protein is altered and the shape of the active site becomes complementary to that of the substrate
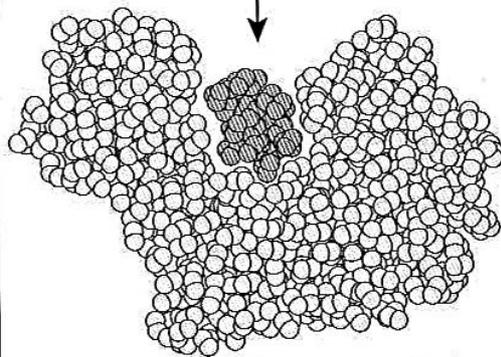
Weakening of bonds in the substrate helps the reaction to occur, converting it into the products. These dissociate from the active site and the enzyme returns to its original conformation
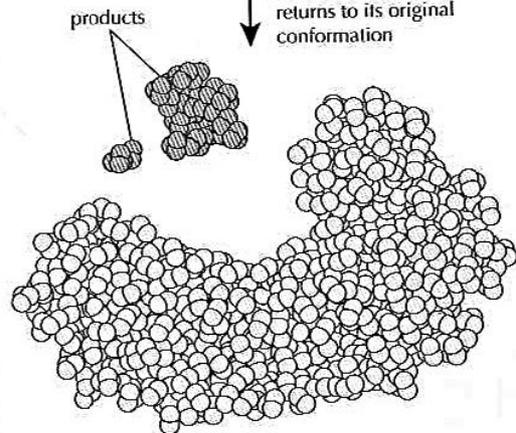
# Enzyme inhibition

Some chemical substances reduce the activity of enzymes or even prevent it completely. These substances are called enzyme inhibitors. Some enzyme inhibitors are **competitive** and some are **non-competitive**. Figures below are a comparison of these types of inhibitor, with an example of each.

## Competitive inhibition

The substrate and inhibitor are chemically very similar

The inhibitor binds to the active site of the enzyme

While the inhibitor occupies the active site, it prevents the substrate from binding and so the activity of the enzyme is prevented until the inhibitor dissociates
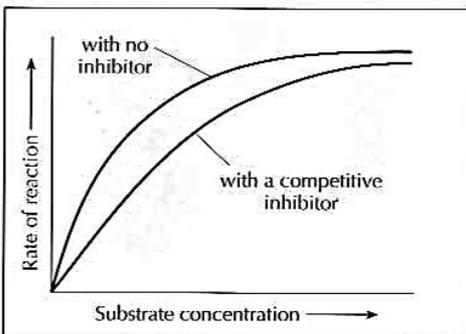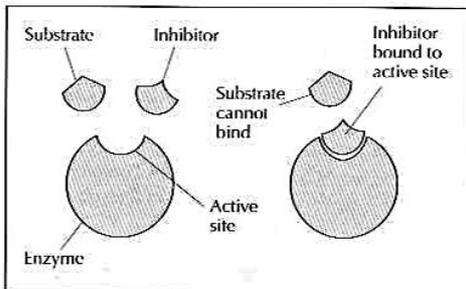


With a fixed low concentration of inhibitor, increases in the substrate concentration gradually reduce the effect of the inhibitor.
The inhibitor and substrate compete for the active site. When the substrate binds to the active site, the inhibitor cannot bind, so the proportion of enzyme molecules that are inhibited becomes less and less. When there are many more substrate molecules than inhibitor molecules, the substrate always wins the competition and binds to the active site. The same maximum enzyme activity rate is then reached as when there is no inhibitor.

### EXAMPLE

Succinate                    Fumarate

$$COO^-$$                    $$COO^-$$
$$|$$                        $$|$$
$$CH_2$$    Succinate   →    $$CH$$          Malonate
$$|$$       dehydrogenase    $$||$$
$$CH_2$$                     $$CH$$          $$COO^-$$
$$|$$                        $$|$$           $$|$$
$$COO^-$$                    $$COO^-$$        $$CH_2$$
                                             $$|$$
Succinate dehydrogenase                      $$COO^-$$
is inhibited by malonate
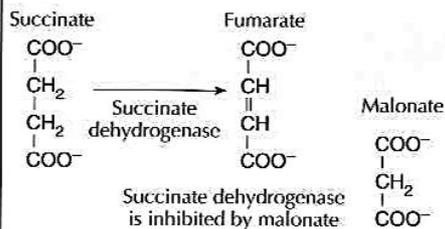
## Non-competitive inhibition

The substrate and active site are not similar

The inhibitor binds to the enzyme at a different site from the active site

The inhibitor changes the conformation of the enzyme. The substrate may still be able to bind, but the active site does not catalyse the reaction, or catalyses it at a slower rate
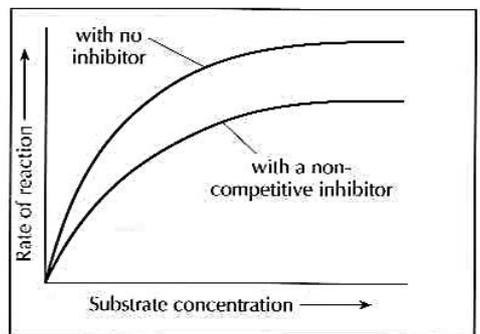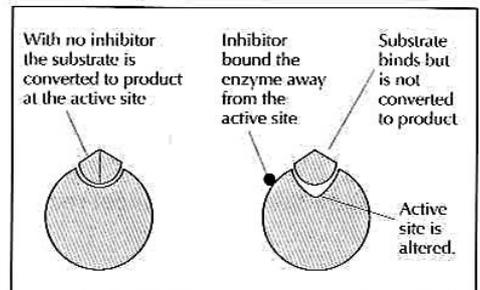


With a fixed low concentration of inhibitor, increases in substrate concentration increase enzyme activity. However, the substrate and inhibitor are not competing for the same site. The substrate cannot prevent the binding of the inhibitor, even at very high substrate concentrations. Some of the enzyme molecules therefore remain inhibited and the maximum enzyme activity rate reached is lower than when there is no inhibitor

### EXAMPLE

Nitric oxide synthase catalyses this reaction:
arginine ⟶ citrulline + nitric oxide

Opioids are chemicals that resemble morphine. They are inhibitors of nitric oxide synthase. They do not resemble arginine and bind to a different site on the enzyme, so they are non-competitive inhibitors. Nitric oxide has many signalling roles in human physiology.

# Controlling metabolic pathways

## METABOLIC PATHWAYS

Metabolic pathways have these features:
- They consist of many chemical reactions that are carried out in a particular sequence.
- An enzyme catalyses each reaction.
- All the reactions occur inside cells.
- Some pathways build up organic compounds (anabolic pathways) and some break them down (catabolic pathways).
- Some metabolic pathways consist of chains of reactions. Glycolysis is an example of a chain of reactions – a chain of ten enzyme-controlled reactions converts glucose into pyruvate.
- Some metabolic pathways consist of cycles of reactions, where a substrate of the cycle is continually regenerated by the cycle. The Krebs cycle is an example.

The figure (opposite) shows the general pattern of reactions in a chain and a cycle.

**Chains and cycles of reactions**

initial substrate → intermediate → intermediate → intermediate → intermediate → intermediate → end product

substrate → intermediate → intermediate → intermediate → intermediate → intermediate → end product / substrate → product
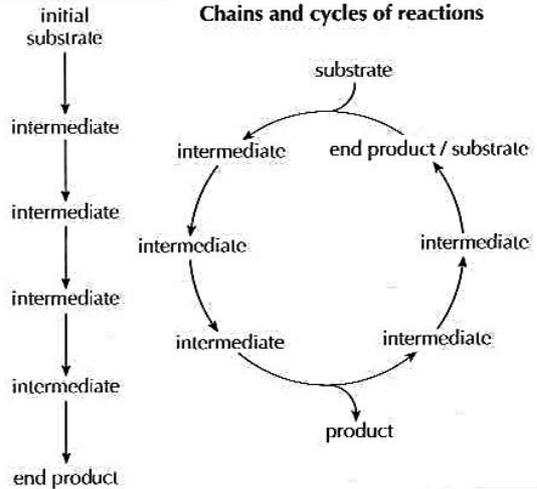
## ALLOSTERY AND THE CONTROL OF METABOLIC PATHWAYS

In many metabolic pathways, the product of the last reaction in the pathway inhibits the enzyme that catalyses the first reaction. This is called **end-product inhibition**. The enzyme that is inhibited by the end products is an example of an **allosteric** enzyme. Allosteric enzymes have two non-overlapping binding sites. One of these is the active site. The other is the allosteric site.

In this case the allosteric site is a binding site for the end product. When it binds, the structure of the enzyme is altered so that the substrate is less likely to bind to the active site. This is how the end-product acts as an inhibitor. Binding of the inhibitor is reversible and if it detaches, the enzyme returns to its original conformation, so the active site can bind the substrate easily again (right).

The advantage of this method of controlling metabolic pathways is that if there is an excess of the end-product the whole pathway is switched off and intermediates do not build up. Conversely, as the level of the end-product falls, more and more of the enzymes that catalyse the first reaction will start to work and the whole pathway will become activated. End product inhibition is an example of negative feedback (see example below).

**End-product inhibition**

Substrate binds to the active site and is converted to the product.

Substrate could bind to the active site as the allosteric site is empty.

Substrate is not likely to bind to the active site as the inhibitor has bound to the allosteric site.

The substrate of the first enzyme in the metabolic pathway is converted by the pathway into an inhibitor of the enzyme.
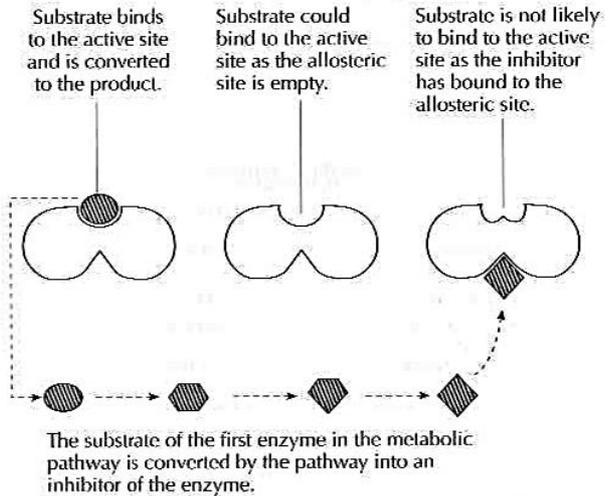
**An example of end product inhibition**

isoleucine is the end product of the pathway and inhibits threonine dehydratase which catalyses the first step
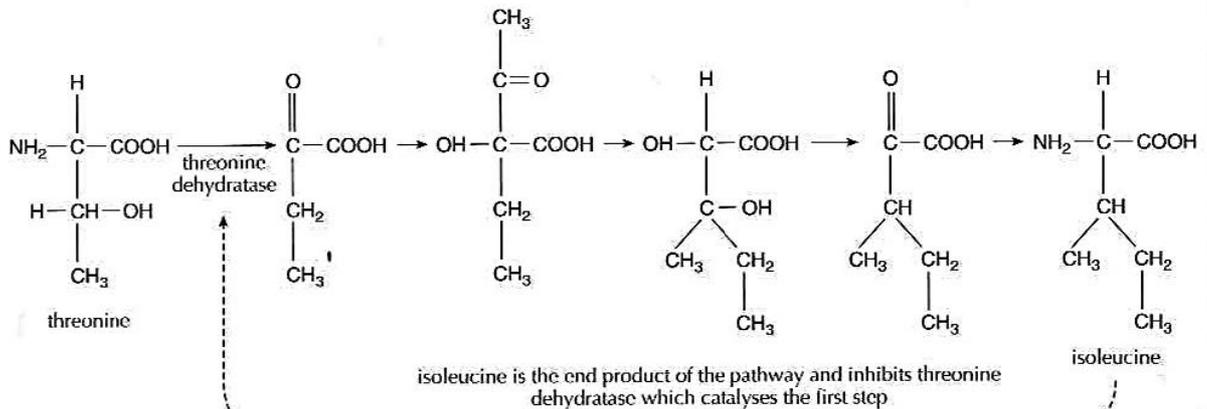
# EXAM QUESTIONS ON TOPIC 7

1  An enzyme experiment was conducted at three different temperatures. The graph shows the amount of substrate remaining each minute after the enzyme was added to the substrate. W shows the results obtained at a temperature of 40 °C.
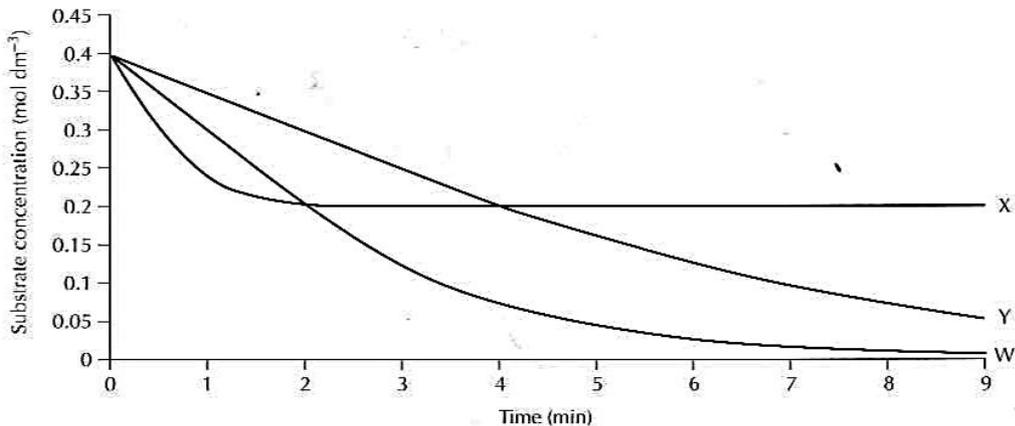


a) (i) Explain whether the temperature used for X was higher or lower than 40 °C.                                    [3]

(ii) Estimate the temperature that was used for Y.                                                                    [2]

b) Draw a curve on the graph to show the expected results of repeating the experiment at 40 °C with

(i) a fixed low concentration of non-competitive inhibitor.                                                          [1]

(ii) a fixed low concentration of competitive inhibitor.                                                             [2]

2  Reverse transcriptase is an enzyme found only in cells infected by certain viruses.

a) ) Distinguish between the 3′ terminal and 5′ terminal in a chain of nucleotides.                                  [2]

b) Nucleic acids contain purines and pyrimidines. Compare purines and pyrimidines.                                   [3]

c) Distinguish between translation and transcription.                                                                [5]

3  The diagram below represents the structure of lysozyme, a protein consisting of a single polypeptide, found in egg white.

a) State the name given to the shape of this type of protein.   [1]

b) State what is meant by the primary structure of a protein.   [1]

c) In the regions labelled X and Y two different types of secondary structure are found.

(i) Identify each type of secondary structure:   [2]

(ii) State the type of bonding that is used to stabilize these structures.   [1]

d) Explain the importance of the tertiary structure of this protein to its function.   [2]
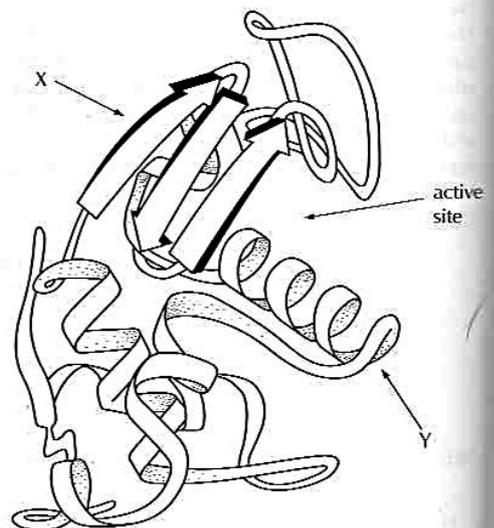
# Glycolysis

## INTRODUCING GLYCOLYSIS

Cell respiration involves the production of ATP using energy released by the oxidation of glucose, fat or other substrates. If glucose is the substrate, the first stage of cell respiration is a metabolic pathway called **glycolysis**. The pathway is catalysed by enzymes in the cytoplasm. Glucose is partially oxidized in the pathway and a small amount of ATP is produced. This partial oxidation is achieved without the use of oxygen, so glycolysis can form part of both aerobic and anaerobic respiration.

## OXIDATION AND REDUCTION IN CELL RESPIRATION

Cell respiration involves many oxidation and reduction reactions. The figure (top right) compares the ways in which chemical substances can be oxidized and reduced. Hydrogen carriers accept hydrogen atoms removed from substrates in cell respiration. The most commonly used hydrogen carrier is NAD⁺ (nicotinamide adenine dinucleotide). Hydrogen atoms consist of one proton and one electron. When two hydrogen atoms are removed from a respiratory substrate, NAD⁺ accepts the electrons from both atoms and the proton from one of them.

$$NAD^+ + 2H \longrightarrow NADH + H^+$$

The figure (right) shows equations for some of the chemical changes that are part of cell respiration. It is possible to use the information in the figure (top right) to deduce whether each of them is an oxidation, a reduction or both.

## CONVERTING GLUCOSE TO PYRUVATE IN GLYCOLYSIS

There are four main stages in glycolysis.

1. Two phosphate groups are added to a molecule of glucose to form hexose biphosphate. Adding a phosphate group is called **phosphorylation**. Two molecules of ATP provide the phosphate groups. The energy level of the hexose is raised by phosphorylation and this makes the subsequent reactions possible.

2. The hexose biphosphate is split to form two molecules of triose phosphate. Splitting molecules is called **lysis**.

3. Two atoms of hydrogen are removed from each triose phosphate molecule. This is an **oxidation**. The energy released by this oxidation is used to link on another phosphate group, producing a 3-carbon compound carrying two phosphate groups. NAD⁺ is the hydrogen carrier that accepts the hydrogen atoms.

4. Pyruvate is formed by removing the two phosphate groups and by passing them to ADP. This results in **ATP formation**.

The figure (right) shows the main stages of glycolysis.

## SUMMARY OF GLYCOLYSIS
- One glucose is converted into two pyruvates.
- Two ATP molecules are used per glucose but four are produced so there is a net yield of two ATP molecules.
- Two NAD⁺ are converted into two NADH + H⁺

### Comparison of oxidation and reduction

| Oxidation reactions | Reduction reactions |
| --- | --- |
| Addition of oxygen atoms to a substance. | Removal of oxygen atoms from a substance. |
| Removal of hydrogen atoms from a substance. | Addition of hydrogen atoms to a substance. |
| Loss of electrons from a substance. | Addition of electrons to a substance. |

### Examples of oxidations and reductions in cell respiration

$$Fe^{3+} + electron \longrightarrow Fe^{2+}$$

$$Fe^{2+} \longrightarrow Fe^{3+} + electron$$

$$succinate + FAD \longrightarrow fumarate + FADH_2$$

$$malate + NAD^+ \longrightarrow oxaloacetate + NADH + H^+$$

$$pyruvate + NADH + H^+ \longrightarrow lactate + NAD^+$$

### Stages of glycolysis

hexose (glucose)

Phosphorylation    2 ATP → 2 ADP

↓

hexose biphosphate

Lysis

↓

2 triose phosphate molecules

Oxidation    2 NAD⁺ → 2 NADH + H⁺

ATP formation    4 ADP → 4 ATP

↓
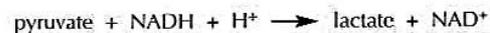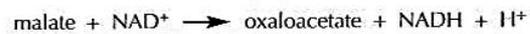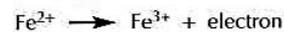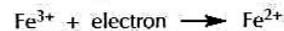
2 pyruvate molecules
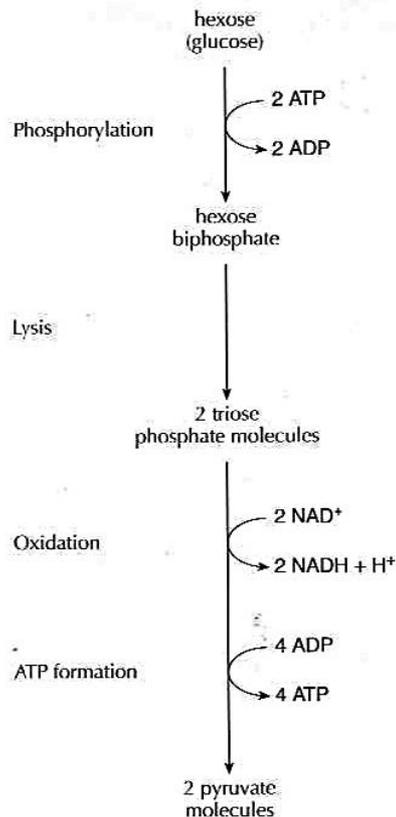
# Krebs cycle

## ANAEROBIC AND AEROBIC RESPIRATION

Glycolysis can occur without oxygen, so it forms the basis of anaerobic cell respiration. Pyruvate produced in glycolysis can only be oxidized further, with the release of more energy from it, if oxygen is available (right). This occurs in the mitochondrion. The first stage is called the **link reaction**. Enzymes in the matrix of the mitochondrion then catalyse a cycle of reactions called the **Krebs cycle**.

glucose

↓ glycolysis

pyruvate $\xrightarrow{\text{no oxygen}}$ ethanol + $CO_2$
or lactate

↓ oxygen available

$CO_2$ and $H_2O$
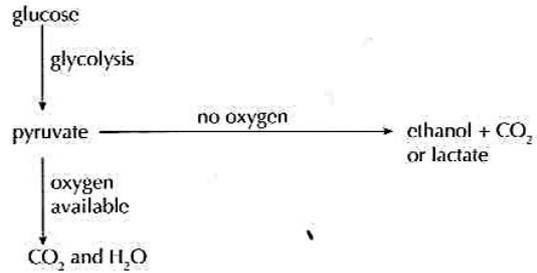
## THE LINK REACTION

Pyruvate from glycolysis is absorbed by the mitochondrion. Enzymes in the matrix of the mitochondrion remove hydrogen and carbon dioxide from the pyruvate. The hydrogen is accepted by $NAD^+$. Removal of hydrogen is oxidation. Removal of carbon dioxide is decarboxylation. The whole conversion is therefore **oxidative decarboxylation**. The product of oxidative decarboxylation of pyruvate is an acetyl group, which is accepted by CoA (right).

**Summary of the link reaction**

$NAD^+$        $NADH + H^+$

pyruvate $\longrightarrow$ acetyl CoA

CoA                    $CO_2$
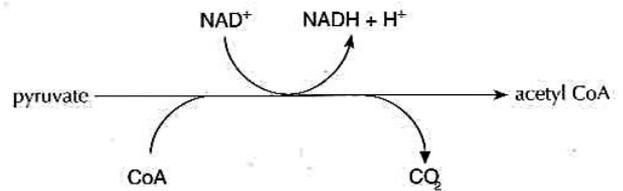
## THE KREBS CYCLE

In the first reaction of the cycle an acetyl group is transferred from acetyl CoA to a four-carbon compound (oxaloacetate) to form a six-carbon compound (citrate). Citrate is converted back into oxaloacetate in the other reactions of the cycle. Three types of reaction are involved.

- Carbon dioxide is removed in two of the reactions. These reactions are **decarboxylations**. The carbon dioxide is a waste product and is excreted together with the carbon dioxide from the link reaction.
- Hydrogen is removed in four of the reactions. These reactions are **oxidations**. In three of the oxidations the hydrogen is accepted by $NAD^+$. In the other oxidation FAD accepts it. These oxidation reactions release energy, much of which is stored by the carriers when they accept hydrogen. This energy is later released by the electron transport chain and used to make ATP.
- ATP is produced directly in one of the reactions.
  This reaction is **substrate-level phosphorylation**.

The figure (right) is a summary of the Krebs cycle.

**Summary of the Krebs cycle**

acetyl CoA        CoA

oxaloacetate ($C_4$)        citrate ($C_6$)

$NAD^+$

$NADH + H^+$

$NADH + H^+$        $CO_2$

$NAD^+$        $C_5$

FADH$_2$

FAD        $C_4$        $NAD^+$

ATP        $NADH + H^+$

ADP        $CO_2$
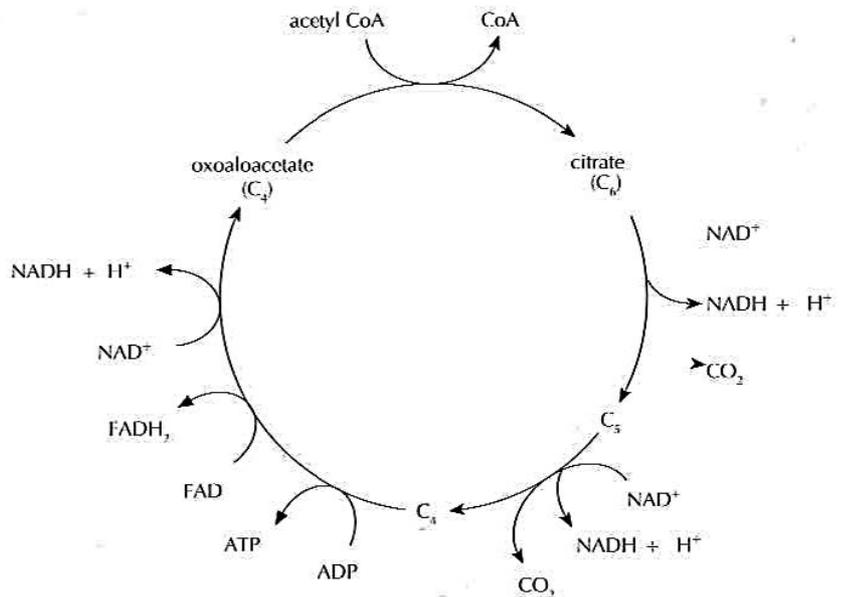
# Oxidative phosphorylation

## THE ELECTRON TRANSPORT CHAIN

The electron transport chain is a series of electron carriers, located in the inner membrane of the mitochondrion. NADH supplies two electrons to the first carrier in the chain. The electrons come from oxidation reactions in earlier stages of cell respiration. The two electrons pass along the chain of carriers because they give up energy each time they pass from one carrier to the next. At three points along the chain enough energy is given up for ATP to be made by ATP synthase. As this ATP production relies on energy released by oxidation it is called **oxidative phosphorylation**. ATP synthase is also located in the inner mitochondrial membrane. $FADH_2$ also feeds electrons into the electron transport chain, but at a slightly later stage than NADH and at only two stages is sufficient energy released for ATP production by electrons from $FADH_2$.

## THE ROLE OF OXYGEN → No Krebs cycle or link reacti

At the end of the electron transport chain the electrons are given to oxygen. At the same time oxygen accepts hydrogen ions, to form water. This happens in the matrix, on the surface of the inner membrane. This is the only stage at which oxygen is used in cell respiration. If oxygen is not available, electron flow along the electron transport chain stops and NADH + $H^+$ cannot be reconverted to $NAD^+$. Supplies of $NAD^+$ in the mitochondrion run out and the link reaction and Krebs cycle cannot continue. Glycolysis can continue because conversion of pyruvate into lactate or ethanol and carbon dioxide produces as much $NAD^+$ as is used in glycolysis. However, whereas aerobic cell respiration gives a yield of about 30 ATP molecules per glucose, glycolysis produces only two. Oxygen thus greatly increases the ATP yield.

The figure (below) shows the electron transport chain and the role of oxygen as the terminal electron acceptor.

### The electron transport chain of mitochondria
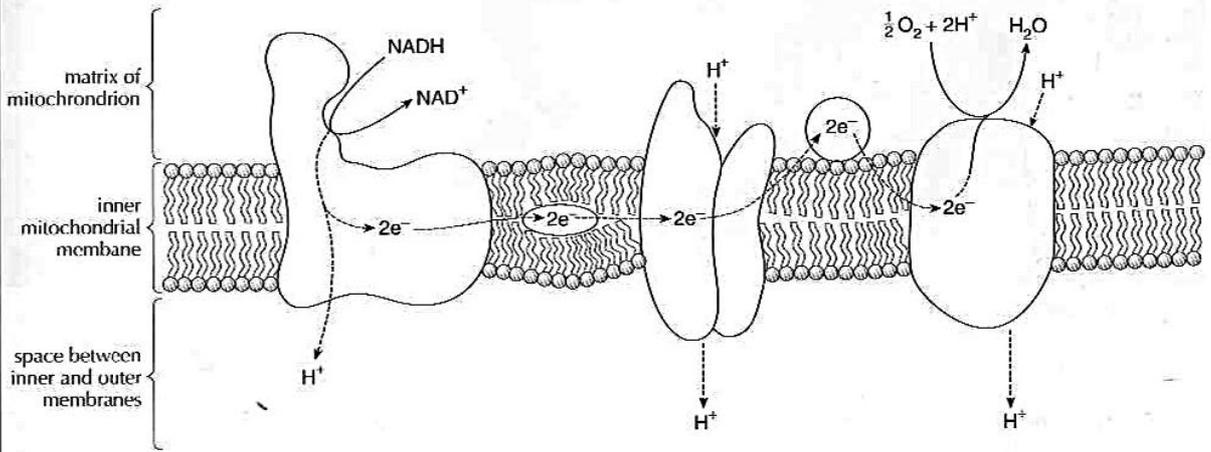


## THE COUPLING OF ELECTRON TRANSPORT TO ATP SYNTHESIS

Energy released as electrons pass along the electron transport chain is used to pump protons ($H^+$) across the inner mitochondrial membrane into the space between the inner and outer membranes. A concentration gradient is formed, which is a store of potential energy. ATP synthase, located in the inner mitochondrial membrane, transports the protons back across the membrane down the concentration gradient. As the protons pass across the membrane they release energy and this is used by ATP synthase to produce ATP. The coupling of ATP synthesis to electron transport via a concentration gradient of protons is called **chemiosmosis**.

The figure (right) shows some features of ATP synthase.

### Structure of ATP synthase

ADP is phosphorylated to ATP at three identical active sites.



These parts of ATP synthase are in a fixed position.

$H^+$ movement across the membrane causes this part of ATP synthase to rotate. This rotation drives ATP production.

inner mitochondrial membrane
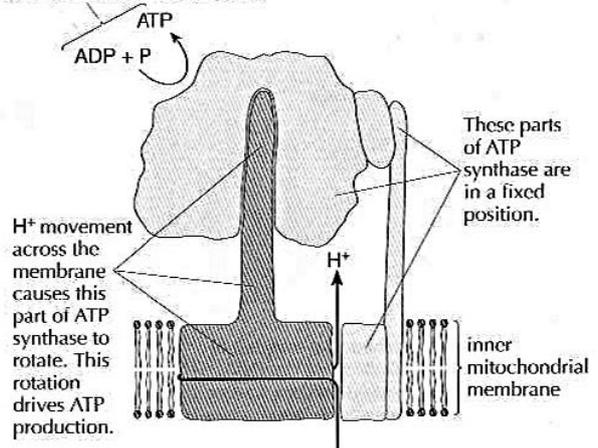
# Mitochondria

The mitochondrion is an excellent example of the relationship between structure and function.
The figure (below) is an electron micrograph of a whole mitochondrion.
The figure (bottom) is a drawing of the same mitochondrion, labelled to show how it is adapted to carry out its function.



0.5 μm



**Outer mitochondrial membrane**
Separates the contents of the mitochondrion from the rest of the cell, creating a compartment with ideal conditions for aerobic respiration.

**Matrix**
Fluid inside the mitochondrian containing enzymes for the Krebs cycle and the link reaction.

70S ribosomes and a naked loop of DNA are present in the matrix.

1–2 μm

**Space between inner and outer membranes**
Protons are pumped into this space by the electron transport chain. Because the space is very small, a high proton concentration can easily be formed in chemiosmosis.

**Inner mitochondrial membrane**
Contains electron transport chains and ATP synthase, which carry out oxidative phosphorylation.

**Cristae**
Tubular or shelf-like projections of the inner membrane which increase the surface area available for oxidative phosphorylation.

# Light and photosynthesis

Photosynthesis is the process that plants, algae and some bacteria use to produce all of the organic compounds that they need.
Photosynthesis involves many chemical reactions. Some of them need a continual supply of light and so are called **light-dependent reactions**. Other reactions need light indirectly, but can carry on for some time in darkness. These are called **light-independent reactions**.
Glucose, amino acids and other organic compounds are produced in the light independent reactions. The light-dependent reactions produce intermediate compounds that are used in the light-independent reactions. In darkness these intermediate compounds are gradually used up.



**Action spectrum of photosynthesis**
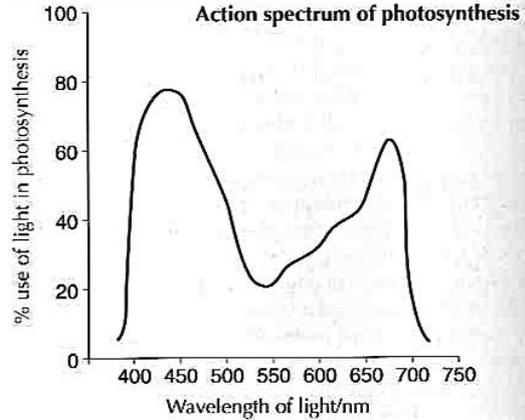
## THE ACTION SPECTRUM used OF PHOTOSYNTHESIS

A spectrum is a range of wavelengths of electromagnetic radiation. The spectrum of light is the range of wavelengths from 400 nm to 700 nm. Each wavelength is a pure colour of light:

        400–525 violet–blue
        525–625 green–yellow
        625–700 orange–red

The efficiency of photosynthesis is not the same in all wavelengths of light. The efficiency is the percentage of light of a wavelength that is used in photosynthesis. The figure (top right) is a graph showing the percentage use of the wavelengths of light in photosynthesis. This graph is called the **action spectrum** of photosynthesis. The graph shows that violet and blue light are used most efficiently and red light is also used efficiently. Green light is used much less efficiently.



**Absorption spectrum of chlorophylls a and b**

KEY
——— chlorophyll a
- - - - - chlorophyll b
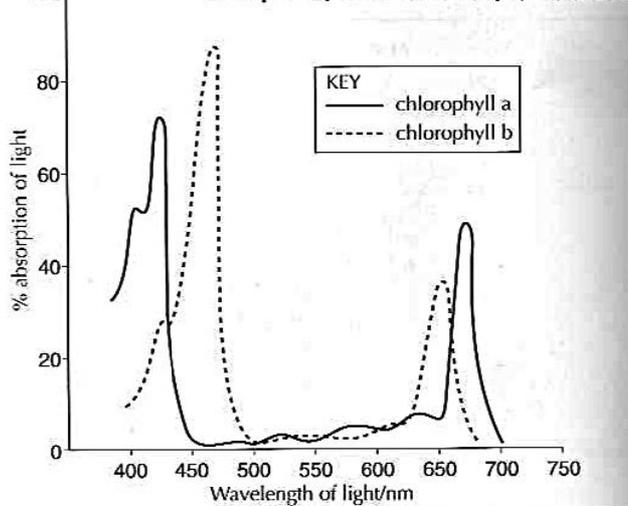
## THE ABSORPTION SPECTRA OF PHOTOSYNTHETIC PIGMENTS absorbed

The action spectrum of photosynthesis is explained by considering the light-absorbing properties of the photosynthetic pigments. Most pigments absorb some wavelengths better than others. The figure (centre right) shows the percentage of the wavelengths of visible light that are absorbed by two common forms of chlorophyll. This graph is called the **absorption spectrum** of these pigments. The graph shows strong similarities with the action spectrum for photosynthesis.

- The greatest absorption is in the violet–blue range.
- There is a also a high level of absorption in the red range of the spectrum.
- There is least absorption in the yellow–green range of the spectrum. Most of this light is reflected.

There are some differences between the action spectrum and the absorption spectra. Whereas little light is absorbed by chlorophylls in the green to yellow range there is some photosynthesis. This is due to accessory pigments, including xanthophylls and carotene, which absorb wavelengths that chlorophyll cannot.

**Action and absorption spectra of an alga**

Some algae contain large amounts of accessory pigments. For example, kelp (*Laminaria saccharina*) contains carotene and fucoxanthin in addition to chlorophylls and so can absorb and use all wavelengths of light with about the same efficiency in photosynthesis. The graph below shows the action and absorption spectra for kelp. The colour of kelp can be deduced from the data.



KEY
——— action spectrum
- - - - - absorption spectrum

Cell respiration and photosynthesis **77**
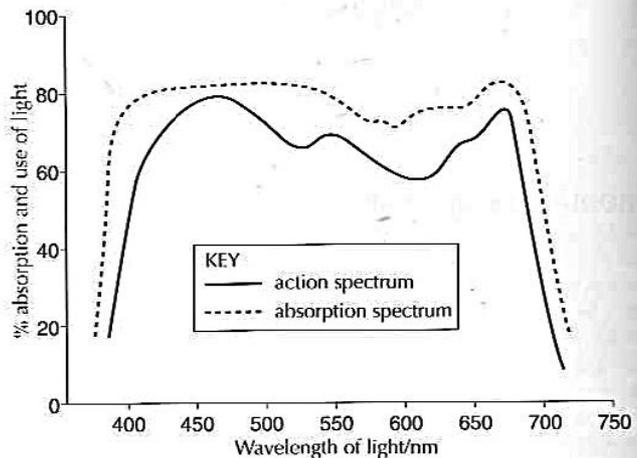
# Light-dependent reactions

## LIGHT ABSORPTION

Chlorophyll absorbs light and the energy from the light raises an electron in the chlorophyll molecule to a higher energy level. The electron at a higher energy level is an **excited electron** and the chlorophyll is **photoactivated**. In single chlorophyll molecules the excited electron soon drops back down to its original level, re-emitting the energy. Chlorophyll is located in thylakoid membranes and is arranged in groups of hundreds of molecules, called **photosystems**. There are two types of photosystem – photosystems I and II. Excited electrons from absorption of photons of light anywhere in the photosystem are passed from molecule to molecule until they reach a special chlorophyll molecule at the reaction centre of the photosystem. This chlorophyll passes the excited electron to a chain of electron carriers.

## PRODUCTION OF ATP

An excited electron from the reaction centre of photosystem II is passed along a chain of carriers in the thylakoid membrane (below). It gives up some of its energy each time that it passes from one carrier to the next. At one stage, enough energy is released to make a molecule of ATP. The coupling of electron transport to ATP synthesis is by chemiosmosis, as in the mitochondrion. Electron flow causes a proton to be pumped across the thylakoid membrane into the fluid space inside the thylakoid. A proton gradient is created. ATP synthase, located in the thylakoid membranes, lets the protons across the membrane down the concentration gradient and uses the energy released to synthesize ATP.

The production of ATP using the energy from an excited electron from Photosystem II is called **non-cyclic photophosphorylation**. An alternative method of photophosphorylation is shown on page 81.



Light-dependent reactions in the thylakoid
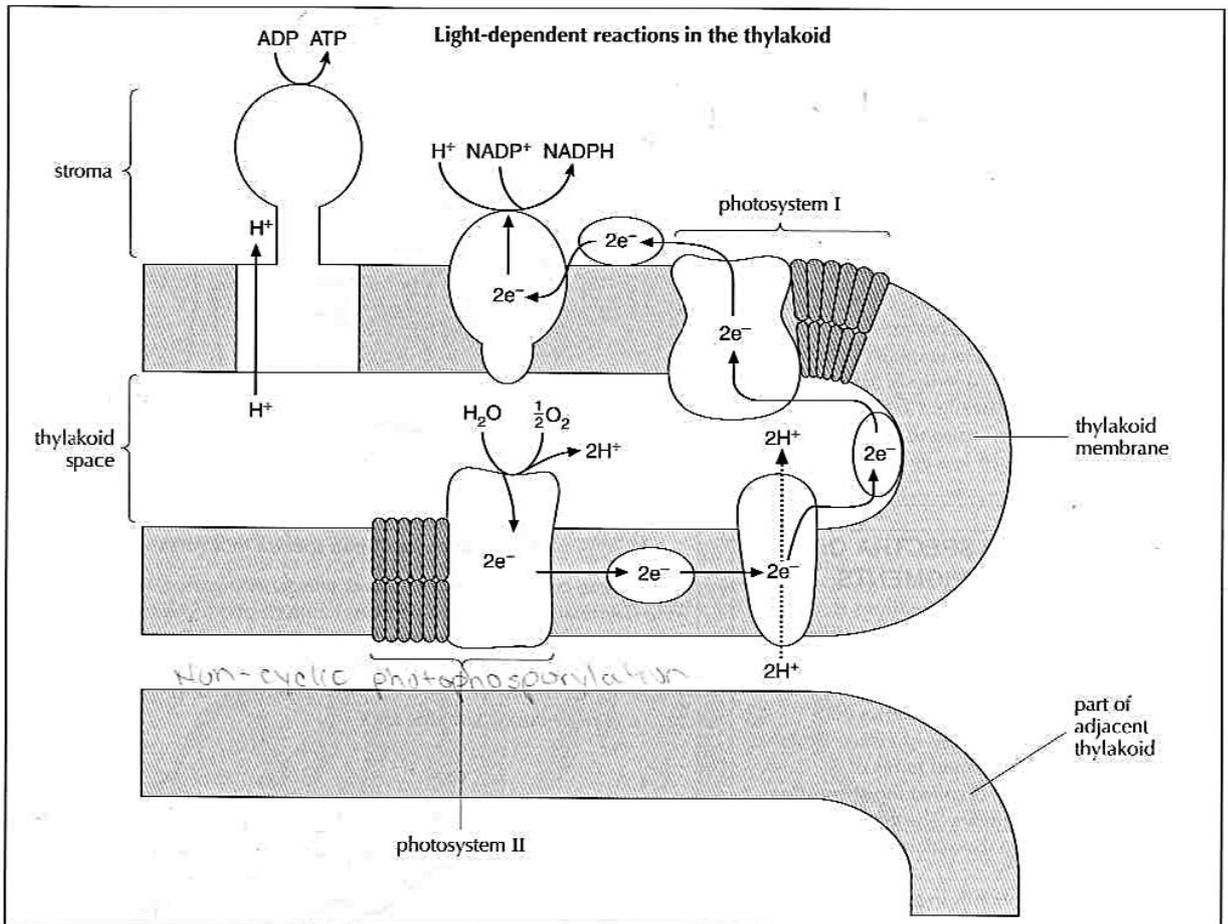
## PRODUCTION OF NADP

After releasing the energy needed to make ATP, the electron that was given away by photosystem II is accepted by photosystem I. The electron replaces one previously given away by photosystem I. With its electron replaced, photosystem I can be photoactivated by absorbing light and then give away another excited electron. This high-energy electron passes along a short chain of carriers to NADP+ in the stroma. NADP+ accepts two high-energy electrons from the electron transport chain and one H+ ion from the stroma, to form NADPH.

## PRODUCTION OF OXYGEN

Photosystem II needs to replace the excited electrons that it gives away. The special chlorophyll molecule at the reaction centre is positively charged after giving away an electron. With the help of an enzyme at the reaction centre, water molecules in the thylakoid space are split and electrons from them are given to chlorophyll. Oxygen and H+ ions are formed as by-products. The splitting of water molecules only happens in the light, so is called **photolysis**. The oxygen produced in photosynthesis is all the result of photolysis of water. Oxygen is a waste product and is excreted.

# Light-independent reactions

## THE CALVIN CYCLE

The light-independent reactions take place within the stroma of the chloroplast. The first reaction involves a five-carbon sugar, ribulose bisphosphate (RuBP). RuBP is also a product of the light independent reactions, which therefore form a cycle, called the **Calvin cycle**. There are many alternative names for the intermediate compounds in the Calvin cycle. Glycerate 3-phosphate is sometimes also called 3-phosphoglycerate. Glycerate 3-phosphate is sometimes abbreviated as GP, which could be confused with glyceraldehyde 3-phosphate, which is a form of triose phosphate or with glucose phosphate. The abbreviation GP should therefore be avoided!

## CARBON FIXATION

Carbon dioxide is an essential substrate in the light-independent reactions. It enters the chloroplast by diffusion. In the stroma of the chloroplast carbon dioxide combines with ribulose bisphosphate (RuBP), a five-carbon sugar, in a carboxylation reaction. The reaction is catalysed by the enzyme ribulose bisphosphate carboxylase, usually called **rubisco**. Large amounts of rubisco are present in the stroma, because it works rather slowly and the reaction that it catalyses is a very important one. The product of the reaction is a six-carbon compound, which immediately splits to form two molecules of glycerate 3-phosphate. This is therefore the first product of carbon fixation.



Summary of the Calvin cycle
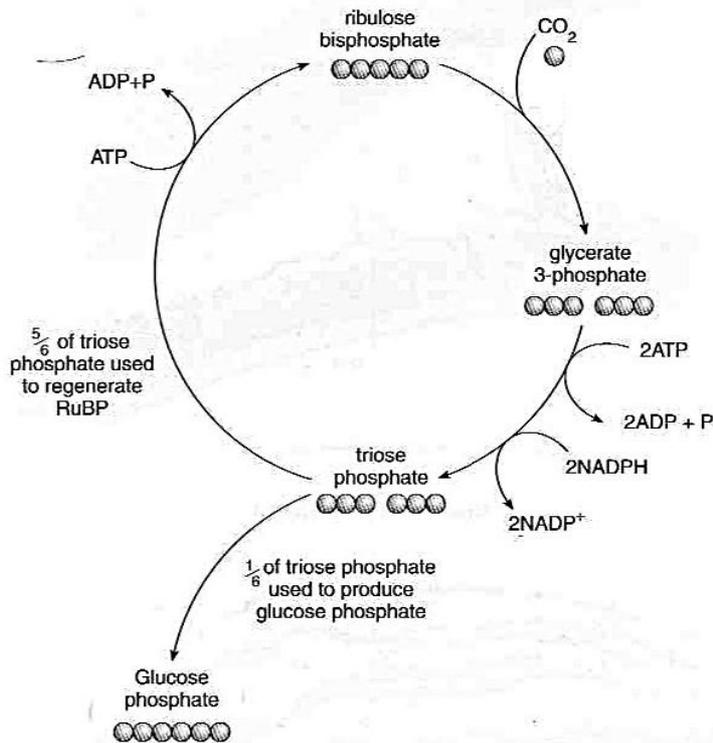
## REGENERATION OF RUBP

For carbon fixation to continue, one RuBP molecule must be produced to replace each one that is used. Triose phosphate is used to regenerate RuBP. Five molecules of triose phosphate are converted by a series of reactions into three molecules of RuBP. This process requires the use of energy in the form of ATP. The reactions can be summarized using equations where only the number of carbon atoms in each sugar molecule is shown.

$$C_3 + C_3 \longrightarrow C_6$$
$$C_6 + C_3 \longrightarrow C_4 + C_5$$
$$C_4 + C_3 \longrightarrow C_7$$
$$C_7 + C_3 \longrightarrow C_5 + C_5$$
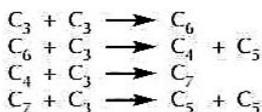
For every six molecules of triose phosphate formed in the light-independent reactions, five must be converted to RuBP.

## SYNTHESIS OF CARBOHYDRATE

Glycerate 3-phosphate, formed in the carbon fixation reaction, is an organic acid. It is converted into a carbohydrate by a reduction reaction. Hydrogen is needed to carry out this reaction and is supplied by NADPH. Energy is also needed and is supplied by ATP. used
NADPH and ATP are produced in the light-dependent reactions of photosynthesis. Glycerate 3-phosphate is reduced to a three-carbon sugar, triose phosphate (TP). Linking together two triose phosphate molecules together produces glucose phosphate. Starch, the storage form of carbohydrate in plants, is formed in the stroma by condensation of many molecules of glucose phosphate.

# Chloroplasts

The chloroplast is another example of close relationship between structure and function. The figure (below) is an electron micrograph of a chloroplast. The figure (bottom) is a drawing of the same chloroplast, labelled to show how it is adapted to carry out its function.



1 µm

**Structure of a chloroplast**



granum

thylakoid (Chlorophyll)
membranes

stroma containing
70S ribsomes and
naked DNA

inner
membrane

outer
membrane

chloroplast
envelope

starch
grain

lipid
droplet
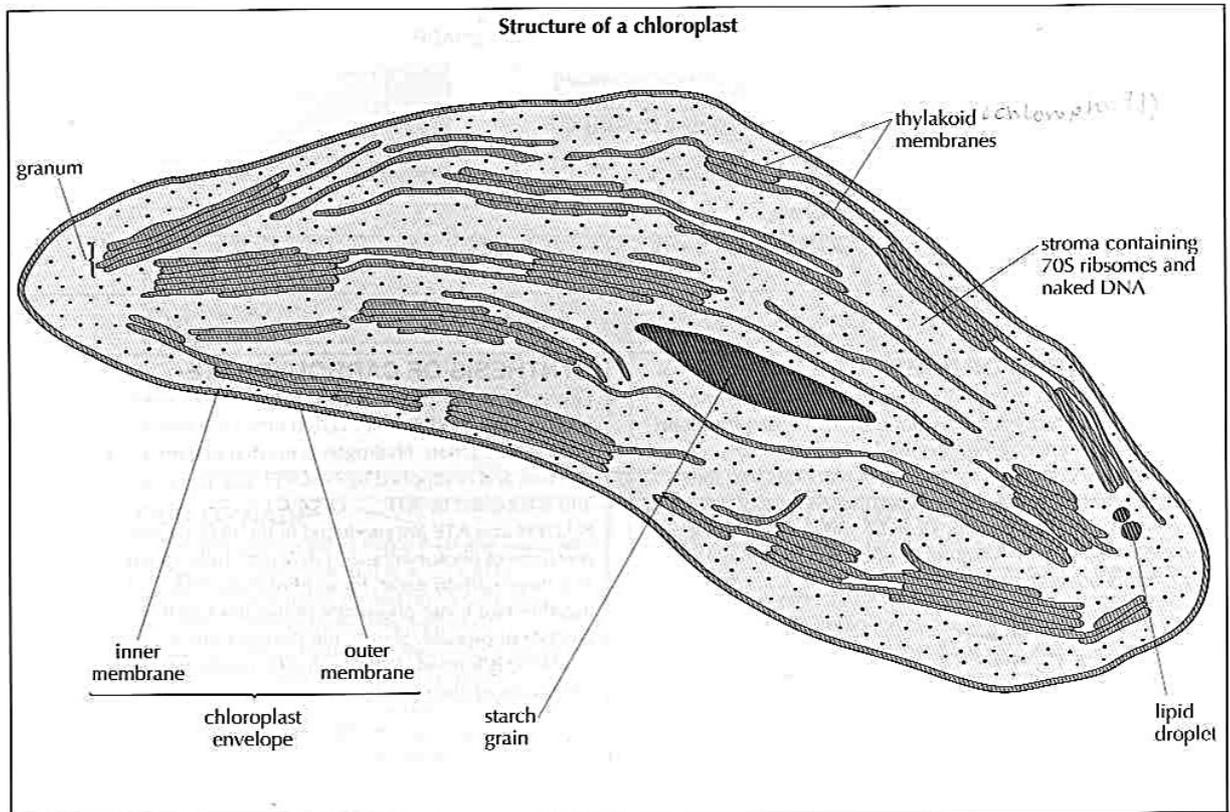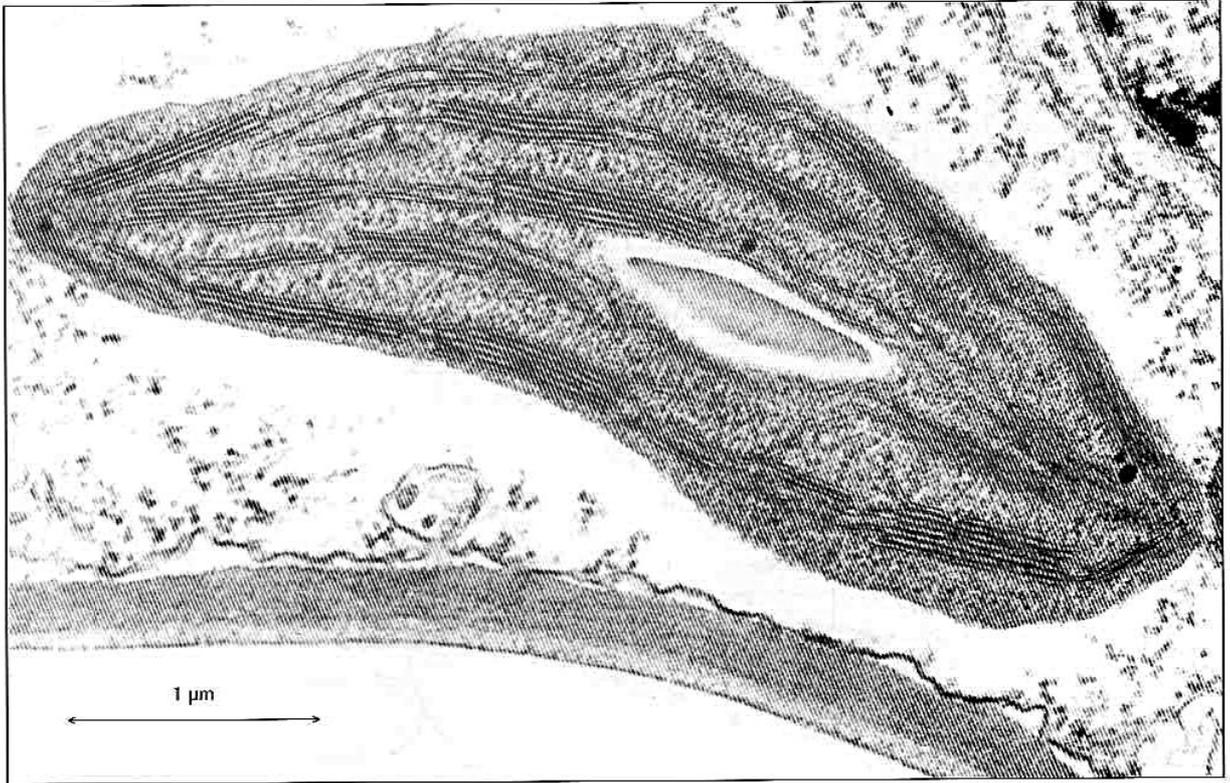
# Limiting factors in photosynthesis

## THE CONCEPT OF LIMITING FACTORS

Light intensity, carbon dioxide concentration and temperature are three factors that can determine the rate of photosynthesis. If the level of one of these factors is changed, the rate of photosynthesis changes. Usually, only changes to one of the factors will affect the rate of photosynthesis in a plant at a particular time. This is the factor that is nearest to its minimum and is called the **limiting factor**. Changing the limiting factor increases or decreases the rate, but changes to the other factors have no effect. This is because photosynthesis is a complex process involving many steps. The overall rate of photosynthesis in a plant is determined by the rate of whichever step is proceeding most slowly at a particular time. This is called the **rate-limiting step**. The three limiting factors affect different rate-limiting steps.

The figures on page 21 show the relationship between each of the limiting factors and the rate of photosynthesis.

## THE EFFECT OF LIGHT INTENSITY

At low light intensities, there is a shortage of the products of the light-dependent reactions – NADPH and ATP. The rate-limiting step in the Calvin cycle is the point where glycerate 3-phosphate is reduced.

At high light intensities some other factor is limiting.

Unless a plant is heavily shaded, or the sun is rising or setting, light intensity is not usually the limiting factor.

## THE EFFECT OF $CO_2$ CONCENTRATION

At low and medium $CO_2$ concentrations, the rate-limiting step in the Calvin cycle is the point where $CO_2$ is fixed to produce glycerate 3-phosphate. RuBP and NADPH accumulate.

At high $CO_2$ concentrations some other factor is limiting.

Because the level of carbon dioxide in the atmosphere is never very high, carbon dioxide concentration is often the limiting factor.

## THE EFFECT OF TEMPERATURE

At low temperatures, all of the enzymes that catalyse the reactions of the Calvin cycle work slowly. NADPH accumulates.

At intermediate temperatures, some other factor is limiting.

At high temperatures, RuBP carboxylase does not work effectively, so the rate-limiting step in the Calvin cycle is the point where $CO_2$ is fixed. NADPH accumulates.

## Results of an investigation into limiting factors

The figure (right) shows the effects of light intensity on the rate of photosynthesis at two different temperatures and two carbon dioxide concentrations. It is possible to deduce which is the limiting factor at the point marked with an arrow (① – ④) on each curve.

KEY
— 30 °C and 0.15% $CO_2$
----- 20 °C and 0.15% $CO_2$
· · · · · 30 °C and 0.035% $CO_2$
∘ ∘ ∘ ∘ 20 °C and 0.035% $CO_2$
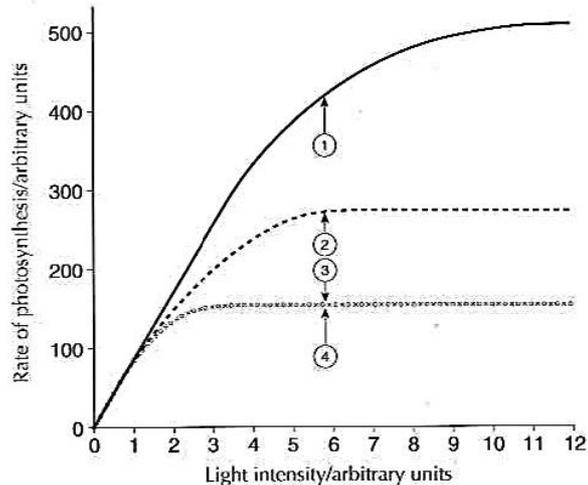


## Summary of cyclic photophosphorylation
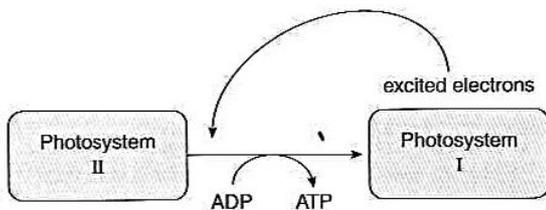


## CYCLIC PHOTOPHOSPHORYLATION

When light is not the limiting factor, NADPH tends to accumulate in the stroma and there is a shortage of NADP+. The normal flow of electrons in the thylakoid membranes is inhibited because NADP+ is needed as a final acceptor of electrons. An alternative route can be used that allows ATP production when NADP+ is not available.

This pathway is called **cyclic photophosphorylation**.

- Photosystem I absorbs light and is photoactivated.
- Excited electrons are passed from photosystem I to a carrier in the chain between photosystem II and photosystem I.
- The electrons pass along the chain of carriers back to photosystem I.
- As the electrons flow along the chain of carriers they cause pumping of protons across the thylakoid membrane.
- A proton gradient is formed and this allows production of ATP by ATP synthase.

The figure (left) shows the pathway used in cyclic photophosphorylation.

1 The electron micrograph below shows part of a plant root cell, including mitochondria.
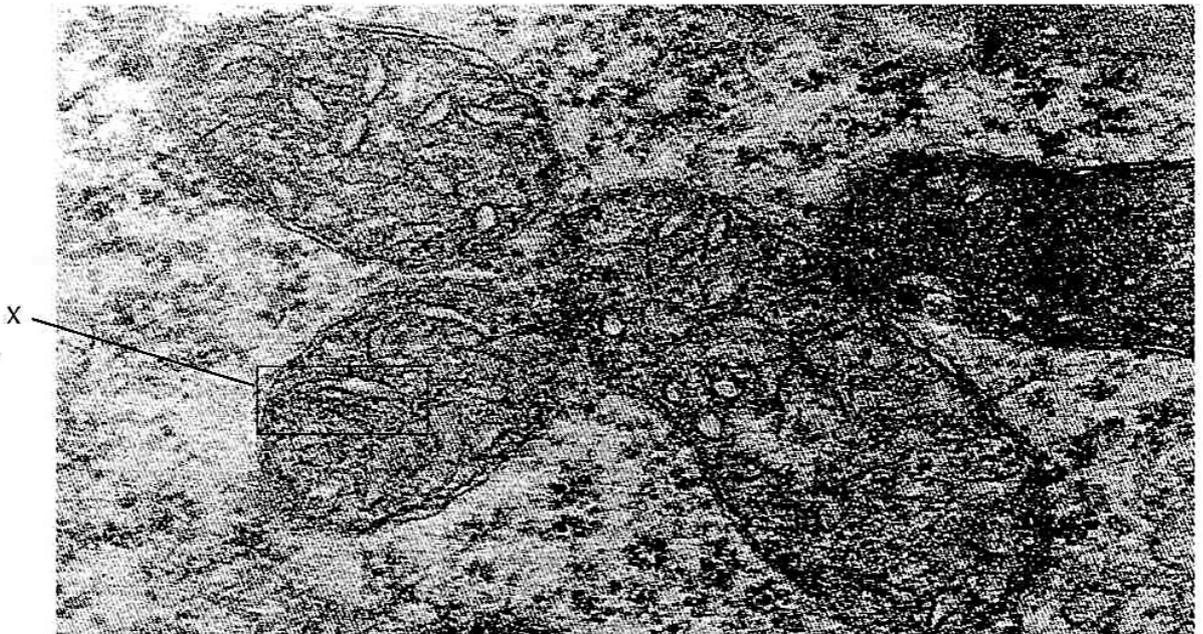


[Source: Dr B. E. Juniper, Dept. of Plant Sciences, University of Oxford]

a) Explain briefly two features that allow the mitochondria in the micrograph to be identified. [2]

b) Redraw the structure of the mitochondrion marked X. [2]

c) Annotate the micrograph (not your drawing) to show one example of

  (i) a region where the Krebs cycle takes place

  (ii) a location of ATP synthetase

  (iii) a region where glycolysis takes place. [3]

2 a) Draw a curve of the action spectrum for photosynthesis on the axis below. [2]
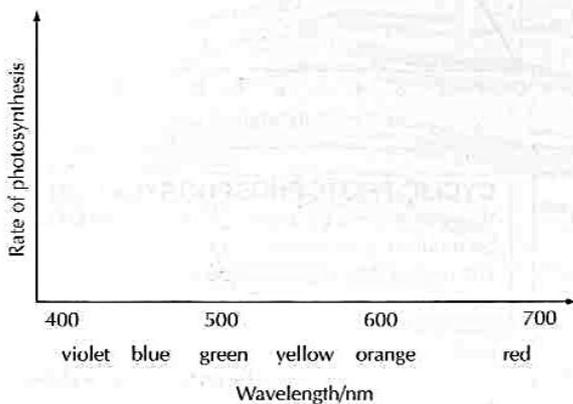


b) Explain the relationship between the action spectrum and the absorption spectra of photosynthetic pigments. [3]

3 a) State two processes that involve chemiosmosis. [2]

b) Explain the need for a membrane in chemiosmosis. [3]

c) Suggest a location where chemiosmosis could occur in prokaryotes. [1]

# Leaf structure and function

## LEAVES AND PHOTOSYNTHESIS

The function of leaves is to produce food for the plant by photosynthesis. The leaf is adapted by its structure to carry out photosynthesis efficiently. On page 5 is a scanning electron micrograph of a leaf. The figure (below) is a plan diagram of tissues in part of a leaf of a dicotyledonous plant to show the adaptations for photosynthesis.

### Tissues of the leaf and their functions

**Palisade mesophyll**—consists of densely packed cylindrical cells with many chloroplasts. This is the main photosynthetic tissue and is positioned near the upper surface where the light intensity is highest

The main part of the leaf is the leaf blade or lamina. It has a large surface area to absorb sunlight but is very thin – only about 0.3 mm. It is composed of four thin tissue layers with veins at intervals.

**Spongy mesophyll**—consists of loosely packed rounded cells with few chloroplasts. This tissue provides the main gas exchange surface so must be near the stomata in the lower epidermis.

## LEAVES AND TRANSPIRATION

Photosynthesis depends on gas exchange over a moist surface. Spongy mesophyll cell walls provide this surface. Water often evaporates from the surface and is lost, in a process called transpiration. *Transpiration is the loss of water vapour from the leaves and stems of plants.* The figure (below) shows adaptations to minimize the amount of transpiration.

**Upper epidermis**—a continuous layer of cells covered by a thick waxy cuticle. Prevents water loss from the upper surface even when heated by sunlight. Lower epidermis in a cooler position has a thinner waxy cuticle

**Xylem**—brings water to replace losses due to transpiration

**Phloem**—transports products of photosynthesis out of the leaf.

Vein is centrally positioned to be close to all cells.

**Stoma**—a pore that allows $CO_2$ for photosynthesis to diffuse in and $O_2$ to diffuse out.

**Guard cells**—this pair of cells can open or close the stoma and so control the amount of transpiration.

## FACTORS AFFECTING TRANSPIRATION

Plants lose water vapour from their stems and leaves by transpiration. The rate of water loss varies depending on internal and external conditions. The main internal condition is whether the stomata are open or closed. The plant hormone **abscisic acid** causes guard cells to close the stomata. Plants produce abscisic acid when they are suffering water stress. External variables are called **abiotic factors** – four of these have an effect on the rate of transpiration.

- Light – guard cells close the stomata in darkness, so transpiration is much greater in the light.
- Temperature – heat is needed for evaporation of water from the surface of spongy mesophyll cells, so as temperature rises the rate of transpiration rises. Higher temperatures also increase the rate of diffusion through the air spaces in the spongy mesophyll, and reduce the relative humidity of the air outside the leaf.
- Humidity – water diffuses out of the leaf when there is a concentration gradient between the air spaces inside the leaf and the air outside. The air spaces are always nearly saturated. The lower the humidity outside the leaf, the steeper the gradient and therefore the faster the rate of transpiration.
- Wind – pockets of air saturated with water vapour tend to form near stomata in still air, which reduce the rate of transpiration. Wind blows the saturated air away and so increases the rate of transpiration.

## TRANSPIRATION IN XEROPHYTES

Plants that are adapted to grow in very dry habitats are called **xerophytes**. *Cereus giganteus*, the saguaro or giant cactus, is an example of a xerophyte. It grows in deserts in Mexico and Arizona and shows many xerophytic adaptations, which help to reduce transpiration.

Vertical stems to absorb sunlight early and late in the day but not at midday when light is most intense.

Very thick waxy cuticle covering the stem.

Spines instead of leaves to reduce the surface area for transpiration.

CAM physiology, which involves opening stomata during the cool nights instead of in the intense heat of the day.
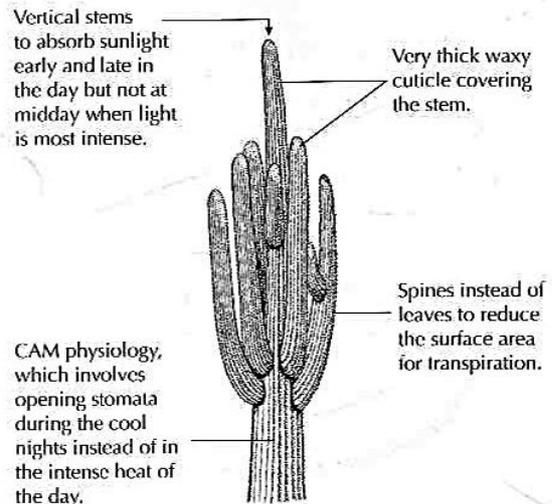
# Transport and support

## MINERAL UPTAKE BY ROOTS

Roots absorb water and mineral ions from the soil.
Plants increase the surface area for absorption by **branching of roots** and the growth of root hairs.

Plants absorb potassium, phosphate, nitrate and other mineral ions from the soil. The concentration of these ions in the soil is usually much lower than inside root cells, so they are absorbed by **active transport**. Root hair cells have mitochondria and protein pumps in their plasma membranes. Most roots only absorb mineral ions if they have a supply of oxygen, because they produce ATP for active transport, by aerobic cell respiration.

The rate of absorption of mineral ions is sometimes limited by the rate at which the ions move through the soil to the root. There are three ways in which ions can move:

- diffusion of mineral ions
- mass flow of water carrying ions, when water drains through the soil
- into fungal hyphae, that grow around plant roots in a mutualistic relationship, and then from the hyphae to the roots.

## STRUCTURE AND FUNCTION OF STEMS

Stems connect the leaves, roots and flowers of plants and transport materials between them using xylem and phloem tissue. Stems support the aerial parts of terrestrial plants. Support is provided in several ways.

- Cells absorb water and high pressure develops inside the cell. This is **cell turgor** and it makes the cell almost rigid.
- Some cells develop thickened cellulose walls, which strengthen the plant.
- Cell walls in xylem tissue are both thickened and lignified making them very strong (above right). Xylem provides support especially in woody stems.

The figure (below) is a plan diagram to show the position of the tissues in the stem of a young dicotyledonous plant.

**Transverse section of a stem**
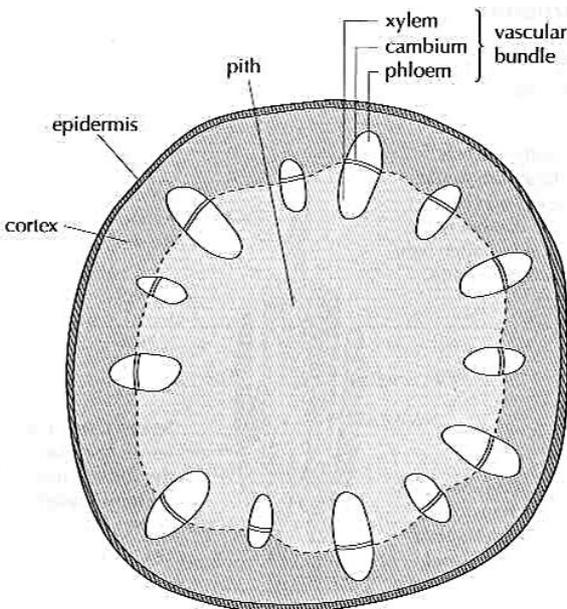


## Structure of xylem vessels



No plasma membranes are present in mature xylem vessels, so water can move in and out freely

Helical or ring-shaped thickenings of the cellulose cell wall are impregnated with lignin. This makes them hard, so that they can resist inward pressures

Lumen of the xylem vessel is filled with sap, as the cytoplasm and the nuclei of the original cells break down. End walls also break down to form a continuous tube

Pores in the outer cellulose cell wall conduct water out of the xylem vessel and into cell walls of adjacent leaf cells

## WATER TRANSPORT THROUGH PLANTS

Xylem vessels contain long unbroken columns of water. When transpiration is occurring, water moves upwards from the roots to the leaves. This flow is called the **transpiration stream**.

The figure (above) shows the structure of a xylem vessel. Mature xylem vessels are dead and the flow of water through them is passive. Heat from the environment provides energy for **evaporation** of water from the cell walls of spongy mesophyll cells in the leaf. The water that evaporates is replaced with water from xylem vessels in the leaf. The water is pulled out of xylem vessels and through pores in spongy mesophyll cell walls by capillary action. Low pressure or suction is created inside xylem vessels when water is pulled out. This is called the **transpiration pull**. The suction extends down through the columns of water in xylem vessels to the roots. These columns of water do not usually break because of the **cohesion** of water molecules. Water molecules are cohesive due the hydrogen bonds between them.

Another process that can help water to move up in xylem vessels is the **adhesion** of water to the wall of the vessel. This is particularly important when sap starts to rise, in xylem vessels of plants that were leafless through the winter. In these plants, xylem vessels are empty in winter and refill in spring. Adhesion also helps prevent the column of water in water-filled xylem vessels from breaking.

## TRANSPORT IN PHLOEM

Sugars and amino acids are transported inside plants by phloem tissue. This process is called **active translocation** because phloem cells have to use energy to make it happen. Sugars and amino acids are loaded into the phloem in parts of the plant called **sources** and are translocated to **sinks**, where they are unloaded. Examples of sources are parts of the plant where photosynthesis is occurring (stems and leaves) and storage organs where the stores are being mobilized. Examples of sinks are roots, growing fruits and the developing seeds inside them.

# Reproduction of flowering plants

## STRUCTURE AND FUNCTION OF FLOWERS

Flowers are the structures used by flowering plants for sexual reproduction. Female gametes are contained in ovules in the ovaries of the flower. Pollen grains, produced by the anthers, contain the male gametes. A zygote is formed by the fusion of a male gamete with a female gamete inside the ovule. This process is called **fertilization**.

Before fertilization, another process called **pollination** must occur. *Pollination is the transfer of pollen from an anther to a stigma.* Pollen grains containing male gametes cannot move without help from an external agent. Most plants use either wind or an animal for pollination. The structure of a flower is adapted to its method of pollination. The figure (below) shows the structure of a flower of *Lamium album*, which is adapted to bee pollination.

Pollen grains germinate on the stigma of the flower and a pollen tube containing the male gametes grows down the style to the ovary. The pollen tube delivers the male gametes to an ovule, which they fertilize.

Fertilized ovules develop into seeds. The figure (bottom) shows the structure of a seed of *Phaseolus multiflorus*. Ovaries containing fertilized ovules develop into fruits. The function of the fruit is **seed dispersal**.

### Structure of *Lamium album* flower
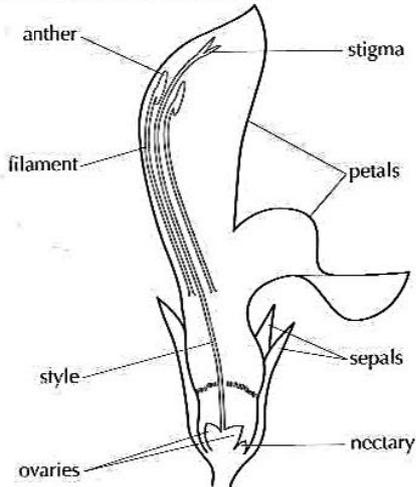


## FACTORS NEEDED FOR SEED GERMINATION

Seeds will not germinate unless external conditions are suitable.

- Water must be available to rehydrate the dry tissues of the seed.
- Oxygen must be available for aerobic cell respiration. Some seeds respire anaerobically if oxygen is not available but ethanol produced in anaerobic respiration usually reaches toxic levels.
- Suitable temperatures are needed. Germination involves enzyme activity and at very low and very high temperatures enzyme activity is too slow. Some seeds remain dormant if temperatures are above or below particular levels, so that they only germinate during favourable times of the year.

The figure (below) shows the structure of a seedling of *Phaseolus multiflorus*, about 2 weeks after the start of germination.

### Structure of a seedling of *Phaseolus multiflorus*
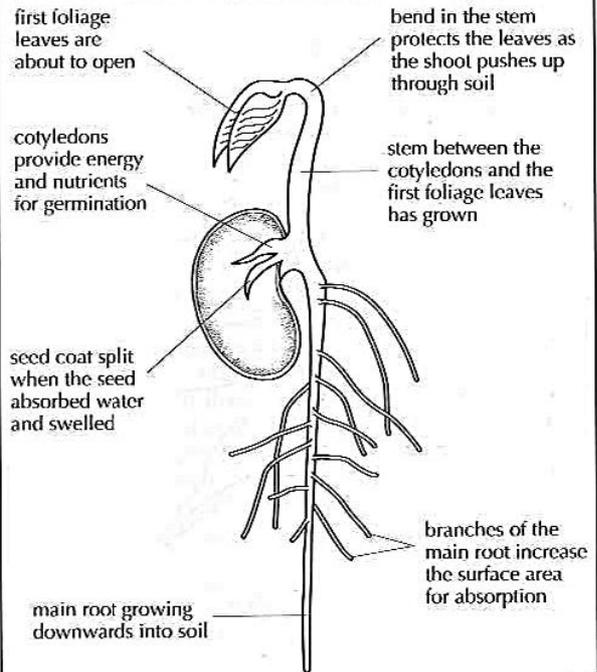


## Structure of a seed of *Phaseolus multiflorus*

### External structure
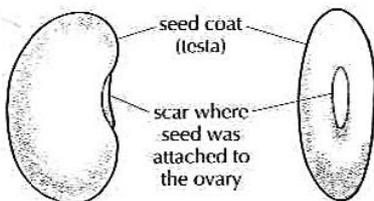


### Internal structure
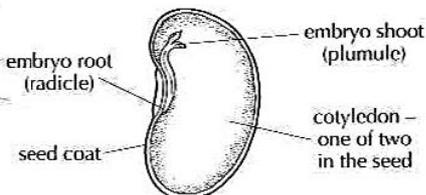


## METABOLIC EVENTS DURING GERMINATION

- The first stage in germination is the absorption of water and the rehydration of living cells in the seed. This allows the cells to become metabolically active.
- Soon after absorbing water, a plant growth hormone called **gibberellin** is produced in the cotyledons of the seed.
- Gibberellin stimulates the production of amylase, which catalyses the digestion of starch into maltose in the food stores of the seed.
- Maltose is transported from the food stores to the growth regions of the seedling, including the embryo root and the embryo shoot.
- Maltose is converted into glucose, which is either used in aerobic cell respiration as a source of energy, or is used to synthesize cellulose or other substances needed for growth.

As soon as the leaves of the seedling have reached light and have opened, photosynthesis can supply the seedling with foods and the food stores of the seed are no longer needed.

# Diversity in plant structure

## MONOCOTYLEDONS AND DICOTYLEDONS

Flowering plants are divided into two groups, according to the number of leaves that the embryo plant has, inside the seed. Monocotyledons have one cotyledon (seed leaf) whereas dicotyledons have two. There are other differences:

| Monocotyledons | Dicotyledons |
|---|---|
| Leaf veins run parallel to each other | Leaf veins form a net-like pattern |
| Vascular bundles are spread through the stem randomly | Vascular bundles are in a ring near the outside of the stem |
| Stamens and other organs in the flower are in multiples of 3 | Stamens and other floral organs are in multiples of 4 or 5 |
| Unbranched roots grow from stems | Roots branch off from other roots |

Examples of plants in each group are shown in the figures (below).

flower has three petals

parallel leaf veins

*Tradescantia pallida*

flower has five petals

branching leaf veins
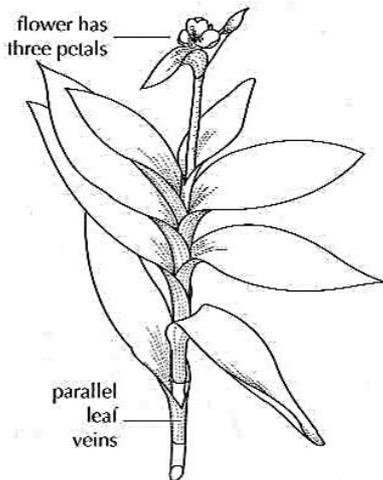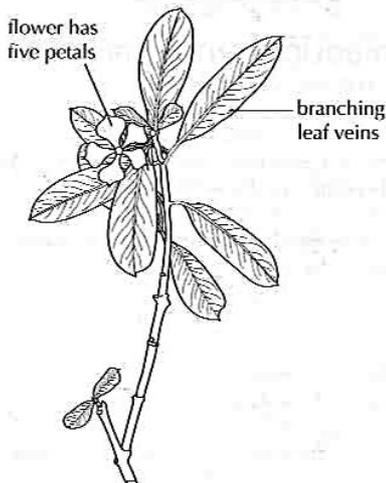
*Caltharanthus roseus*

## MODIFIED ROOTS, STEMS AND LEAVES

The normal functions of the roots, stems and leaves of plants have been described on the previous pages. In some plants, these organs have become modified for other functions.

### 1. Bulbs

In some monocotyledon plants, leaf bases grow to form an underground organ called a bulb (below).
Plants use bulbs for food storage. They can be identified from the series of leaf bases fitting inside each other, with a central shoot apical meristem.

small new bulb, developed from an axillary bud that will eventually separate and form a new plant.

fleshy leaves used for food storage

terminal bud from which leaves grow

stem of bulb

roots
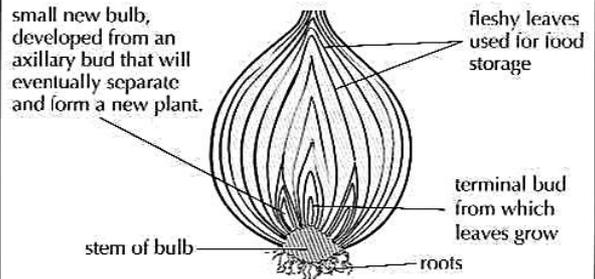
### 2. Stem tubers

In some dicotyledon plants, stems grow downwards into the soil and sections of them grow into stem tubers (below). They are used for food storage. They can be identified as stems because despite being swollen their vascular bundles are arranged in a ring.

Leaves produce food by photosynthesis.

Phloem in stems transports food to storage organs.

Tuber grows and stores food.
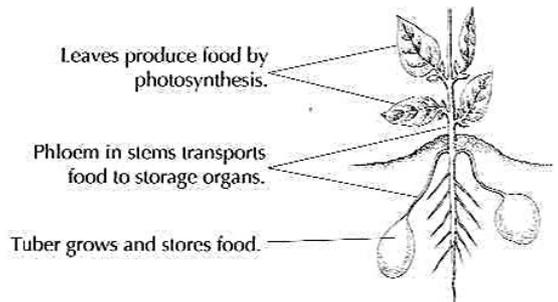
### 3. Storage roots

Some roots become swollen with stores of food (below). They can easily be identified from their shape and from vascular tissue being in the centre.

tendril

Carrot
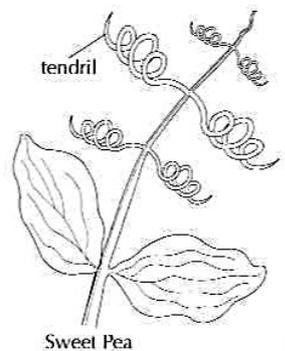
Sweet Pea

### 4. Tendrils

Tendrils are narrow outgrowths from leaves that rotate through the air until they touch a solid support, to which they attach, allowing the plant to climb upwards (above).

# Growth and development in plants

## APICAL AND LATERAL MERISTEMS

Plants have regions where cells continue to divide and grow, often throughout the life of the plant. These regions are called **meristems**. Flowering plants all have meristems at the tip of the root and the tip of the stem (below). These are called **apical meristems** as they are at the apex of the root and stem. Growth in apical meristems allows roots and stems to elongate. The shoot apical meristem also produces new leaves and flowers.

Many dicotyledonous plants also develop **lateral meristems**. In young stems, this consists of cambium in the vascular bundles, but as the stem grows older, a complete ring of cambium forms.

A similar lateral meristem forms in older roots. Growth in lateral meristems makes roots and stems thicker, with extra xylem and phloem tissue. The growth in thickness of tree trunks is due to the lateral meristem, inside the bark.
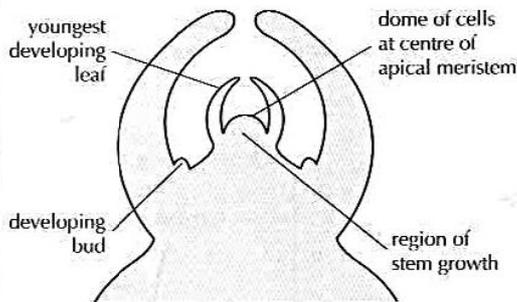


## PHOTOPERIODIC CONTROL OF FLOWERING

Some plants only flower at the time of year when days are short and other plants only flower when the days are long. They are called short-day plants and long-day plants. Experiments have shown that it is not the length of day but the length of night that is significant. For example, chrysanthemums are short-day plants and only flower when they receive a long continuous period of darkness (below). They therefore naturally flower in the autumn (fall). Growers can produce pots of flowering chrysanthemums at all times of the year by keeping them in greenhouses with blinds. When the nights are not long enough to induce flowering, the blinds are closed to extend the nights artificially. In a similar way, petunias, which are long-day plants, can be induced to flower at times of the year when the days are short by being given extra light in greenhouses to reduce the length of the nights.

**Response of chrysanthemums to different light/dark regimes**
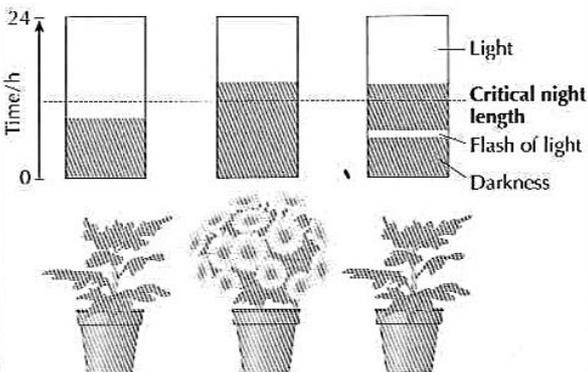


## AUXIN AND PHOTOTROPISM

Plants use hormones to control their growth and their development. An example of a plant hormone is auxin, which acts as a growth promoter. It does this by causing secretion of hydrogen ions into cell walls, which loosens connections between cellulose fibres, allowing cell expansion.

One of the processes that auxin controls is phototropism – directional growth in response to the source of light. Shoot tips can detect the source of the brightest light. They also produce auxin. According to a long-standing theory, auxin is redistributed in the shoot tip from the lighter side to the shadier side. It then promotes more growth on the shadier side, causing the shoot to bend towards the light.

Molecular mechanisms for the action of auxin are being discovered. There are pumps in the plasma membrane called auxin efflux carriers. These are distributed unevenly and so can redistribute auxin in a tissue. Plant cells contain an auxin receptor. When auxin binds to it, transcription of specific genes is promoted, which affect the growth of the cell in the ways described above.

## PHYTOCHROME AND PHOTOPERIODISM

Plants can measure the length of periods of dark to an accuracy of a few minutes. They do this using a pigment in their leaves called **phytochrome**, which exists in two interconvertible forms. One form is called $P_r$ because it absorbs red light with a wavelength of 660 nm. $P_r$ is the inactive form of phytochrome. When it absorbs red light it is rapidly converted into the active form, called $P_{fr}$. This form can absorb far red light with a wavelength of 730 nm and is then rapidly converted back to $P_r$. In normal daylight there is much more red light than far red light so phytochrome exists in the active $P_{fr}$ form. In darkness $P_{fr}$ reverts very slowly to $P_r$ (above). This gradual reversion process is probably how the length of the dark period is timed. Enough $P_{fr}$ remains in long-day plants at the end of short nights to stimulate flowering. In *Arabidopsis*, which is a long-day plant, a protein has been found to which $P_{fr}$ binds. This protein probably acts as a transcription factor, causing genes involved in flowering to be switched on. In short day plants $P_{fr}$ presumably acts as an inhibitor of flowering. At the end of long nights, enough $P_{fr}$ has been converted to $P_r$ to allow flowering to occur.

**Interconversions of phytochrome**
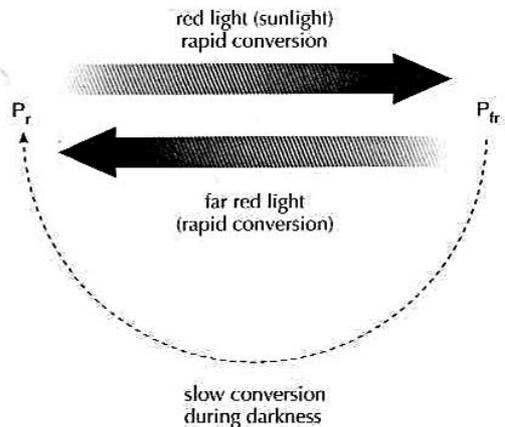
# EXAM QUESTIONS ON TOPIC 9

1 Control of flowering in long-day and short-day plants involves inter-conversion of phytochrome between its two forms, $P_r$ and $P_{fr}$.

   a) State whether phytochrome is in the $P_r$ or $P_{fr}$ form at the end of the day (sunset) in

      (i) long-day plants       [1]

      (ii) short-day plants       [1]

   b) Explain how long-day and short-day plants time the length of the night.       [2]

   c) Distinguish between the effect of $P_{fr}$ in long-day and short-day plants.       [2]

2 Flowering plants (angiospermophytes) are classified into two groups: monocotyledons and dicotyledons.

   a) Outline three differences between monocotyledons and dicotyledons.       [3]

   b) Distinguish between growth due to apical and lateral meristems in the stems of dicotyledons.       [2]

   c) Monocotyledons do not have lateral meristems. Predict the consequences for monocotyledons of not having lateral meristems.       [2]

3 $C_3$ and CAM plants both need $CO_2$ for photosynthesis. They take in $CO_2$ through microscopic pores called stomata. The stomata can vary from being fully closed (0% open) to fully open (100% open). The circular graph below shows the width of opening of stomata during a 24 hour period in a $C_3$ plant and a CAM plant.
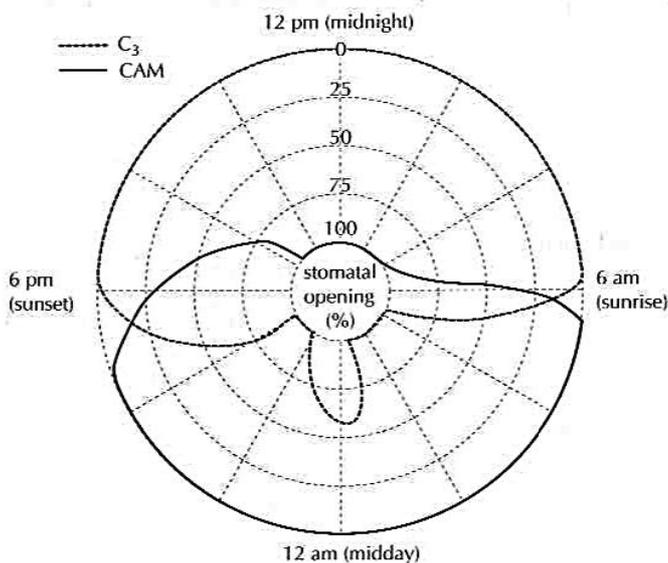


   a) Identify the hours during which stomata were fully closed in

      (i) the $C_3$ plant       [1]

      (ii) the CAM plant       [1]

   b) One of the two plants is a xerophyte.
      Use the data in the graph to predict whether the $C_3$ plant or the CAM plant is the xerophyte.       [2]

   c) (i) Outline the changes in the stomata of the $C_3$ plant shown in the graph between 11.00 am. and 2.00 pm.       [2]

      (ii) Suggest a reason for the changes.       [1]

# Mendel's law of independent assortment

Gregor Mendel discovered the Law of Segregation by doing monohybrid crosses with pea plants. He discovered another law of inheritance by doing crosses in which the parents differed in two characteristics, that are controlled by two different genes. These are called **dihybrid crosses**. Mendel did his dihybrid crosses with pea plants. An example of one of his crosses is shown below. The parents in this cross differ in seed shape, controlled by one gene, and in seed colour, controlled by a different gene.

**KEY TO SYMBOLS**

S = allele for smooth seed.
s = allele for wrinkled seed.
Y = allele for yellow seed.
y = allele for green seed.



P genotype → SSYY / ssyy
phenotype → smooth yellow seed / wrinkled green seed

Pea plants contain two copies of each gene.

gametes → SY / sy

Gametes only contain one copy of each gene.

F₁ genotype → SsYy
phenotype → smooth yellow seed

The alleles for smooth seed and yellow seed are dominant so all of the F₁ have smooth yellow seeds.

gametes → SY Sy sY sy

One copy of each gene is again passed on in the gametes, but as the F₁ plants are heterozygous for both genes there are four possible combinations of alleles.



F₂ genotypes and phenotypes

male gametes / female gametes

SSYY smooth yellow
SSYy smooth yellow / SSyY smooth yellow
SsYY smooth yellow / SSyy smooth green / sSYY smooth yellow
SsYy smooth yellow / SsyY smooth yellow / sSYy smooth yellow / sSyY smooth yellow
Ssyy smooth green / ssYY wrinkled yellow / sSyy smooth green
ssYy wrinkled yellow / ssyY wrinkled yellow
ssyy wrinkled green

The phenotypic ratio in the F₂ generation is
9 smooth yellow:
3 smooth green:
3 wrinkled yellow:
1 wrinkled green

The 9:3:3:1 ratio shows that the four types of gametes are all equally common. The inheritance of the two genes is separate. *The presence of an allele of one of the genes in a gamete has no influence over which allele of the other gene is present in the gamete.* This is Mendel's Law of Independent Assortment.

A Punnett grid is the best way to show the genotypes and phenotypes in a dihybrid cross.

# Dihybrid crosses

## PREDICTING RATIOS IN DIHYBRID RATIOS

The 9:3:3:1 ratio is often found when parents that are heterozygous for two genes are crossed together. The ratio is the product of two 3:1 ratios – each of the two genes would give a 3:1 ratio in a monohybrid cross between two heterozygous parents. In a dihybrid cross they follow Mendel's Law of Independent Assortment because they are unlinked.

Dihybrid crosses can give other ratios if:
- either of the genes has codominant alleles,
- either of the parents is homozygous for one/both of the genes,
- either of the genes is sex linked. Sex-linked genes are located on sex chromosomes instead of on autosomes (non-sex chromosomes).

The figure (right) shows ratios that these types of genes could give. Another cause of unusual ratios is interaction between genes. The figure (below) shows an example of a dihybrid cross where there is interaction between genes.

**Possible ratios in dihybrid crosses**

| | 3 | 1 |
|---|---|---|
| 3 | 9 | 3 |
| 1 | 3 | 1 |

| | 1 | 2 | 1 |
|---|---|---|---|
| 3 | 3 | 6 | 3 |
| 1 | 1 | 2 | 1 |

| | 1 | 1 |
|---|---|---|
| 3 | 3 | 3 |
| 1 | 1 | 1 |

| | 1 | 1 |
|---|---|---|
| 1 | 1 | 1 |
| 2 | 2 | 2 |
| 1 | 1 | 1 |
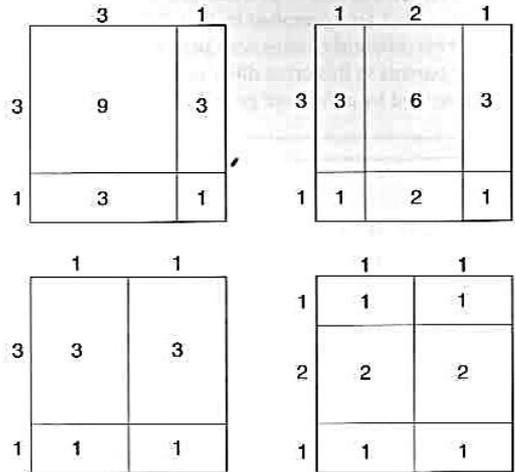


P genotypes CcAa × CcAa

phenotypes agouti agouti

Two genes in mice affect coat colour. One gene controls whether the coat is coloured or not. The other gene controls the colour.

KEY

C = allele for coloured coat
c = allele for albino coat
A = allele for agouti coat
a = allele for black coat

Agouti is the normal colour of wild mice. Each hair has black and white bands so the overall colour is grey.

Punnett square gametes: CA, Ca, cA, ca

| | CCAA agouti | CCAa agouti | CcAA agouti | CcAa agouti |
| CCAa agouti | CCaa black | CcAa agouti | Ccaa black |
| CcAA agouti | CcAa agouti | ccAA albino | ccAa albino |
| CcAa agouti | Ccaa black | ccAa albino | ccaa albino |

9 agouti
3 black
4 albino

All mice that are cc are albino because they are unable to produce pigment in the hairs in their coat.

90 Genetics
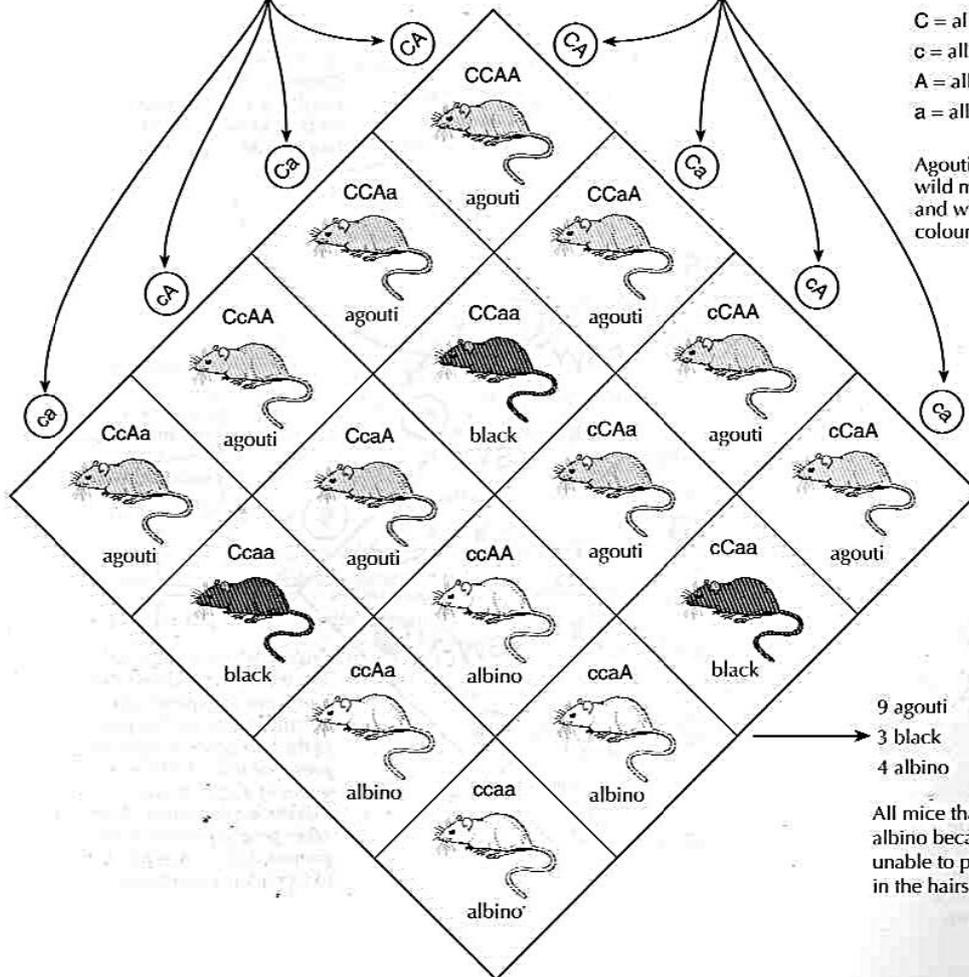
# Polygenic inheritance

## THE DISCOVERY OF POLYGENIC INHERITANCE

Some characteristics are influenced by more than one gene. This is called polygenic inheritance. Gregor Mendel discovered an example of **polygenic inheritance**, when he crossed a purple-flowered species of bean with a white-flowered species. The $F_1$ offspring were all purple, so he expected a 3:1 ratio of purple to white flowers in the $F_2$ offspring. Instead, he found a much smaller proportion of white flowers and a wide variety of shades of purple flower. Mendel suggested that two or three genes might be involved. If these were codominant genes, each with two alleles, one for purple flowers ($A^P$ and $B^P$) and one for white ($A^W$ and $B^W$), there could be five shades of flower colour (right).

## POLYGENIC INHERITANCE AND CONTINUOUS VARIATION

Most examples of polygenic inheritance involve more than two genes with codominant alleles. As the number of genes involved increases, the number of possible phenotypes increases. Eventually, it becomes impossible to divide individuals into discrete groups – the variation is continuous.

**Results of a cross between red and white flowered beans**



## EXAMPLES OF POLYGENIC INHERITANCE
### Grain colour in wheat

Wheat grains vary in colour from white to dark red, depending on the amount of a red pigment they contain. Three genes control the colour. Each gene has two alleles, one that causes pigment production and one that does not. Wheat grains can therefore have between 0 and 6 alleles for pigment production. The figure (right) shows the expected distribution of grain colour from a cross between two plants that are heterozygous for each of the three genes.

### Skin colour in humans

The colour of human skin depends on the amount of the black pigment melanin in it. There is a continuous distribution of skin colour from very pale (little melanin) to black (much melanin). At least four and possibly more genes are involved, each with alleles that promote melanin production and alleles that do not. There is therefore a wide range of possible genotypes with anything from no alleles promoting melanin production to many.
The figure (below) shows humans with a range of skin colour.

**Distribution of grain colour in wheat**
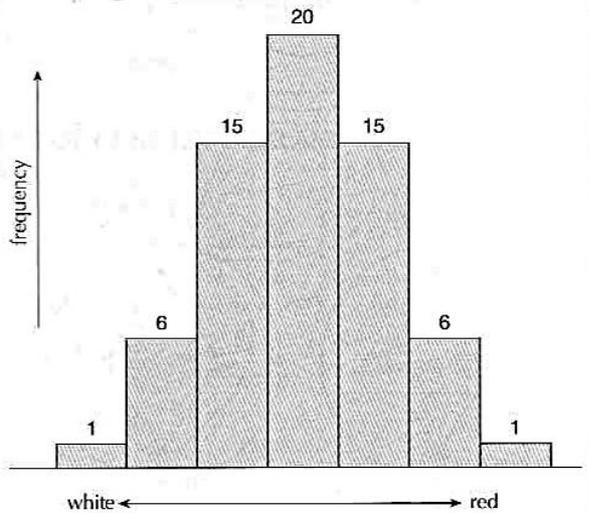


**Skin colour variation in humans**

# Genes – linked and unlinked

## UNLINKED GENES

Mendel's law of independent assortment can be explained in terms of chromosome movements during meiosis. If pairs of genes are located on different types of chromosome, when homologous chromosomes pair up in meiosis the genes are on different pairs. The pairs of homologous chromosomes are called **bivalents**. The bivalents are orientated randomly on the equator, so the pole to which alleles on other bivalents are moving does not affect the pole to which alleles on a bivalent move. Random orientation of bivalents allows combinations of alleles to be broken up, so that new combinations can be formed when gametes fuse during fertilization.

If two parents with the genotypes AABB and aabb are crossed together, the gametes that they produce (AB and ab) will fuse together to give an $F_1$ hybrid with the genotype AaBb. The figure below shows the possible gametes that could be produced by meiosis in this $F_1$ hybrid. The parents could not have produced two of the gametes (Ab and aB).

## GENE LINKAGE

Some pairs of genes do not follow the law of independent assortment. The expected 9:3:3:1 ratio is not found when parents that are heterozygous for the two genes are crossed. The figure (below) shows the first example of this to be discovered. The results show that there were more offspring than expected with the parental character combinations – purple long and red round. There were fewer than expected with the new combinations – purple round and red long. Combinations of genes tend to be inherited together. This is called **gene linkage**.

Gene linkage is caused by pairs of genes being located on the same type of chromosome. New combinations of alleles can only be produced if DNA is swapped between chromatids. This is called **recombination** and involves a special process called **crossing over**, which happens during the early stages of meiosis. Individuals that have a different combination of characters from parents, as a result of crossing over, are called **recombinants**.



**Independent assortment of unlinked genes**



**Gene linkage in *Lathyrus odoratus***

| Expected $F_2$ ratio | 9 purple long | 3 purple round | 3 red long | 1 red round |
|---|---|---|---|---|
| Expected results (6952 plants in total) | 3910.5 | 1303.5 | 1303.5 | 434.5 |
| Observed results | 4831 | 390 | 393 | 1338 |
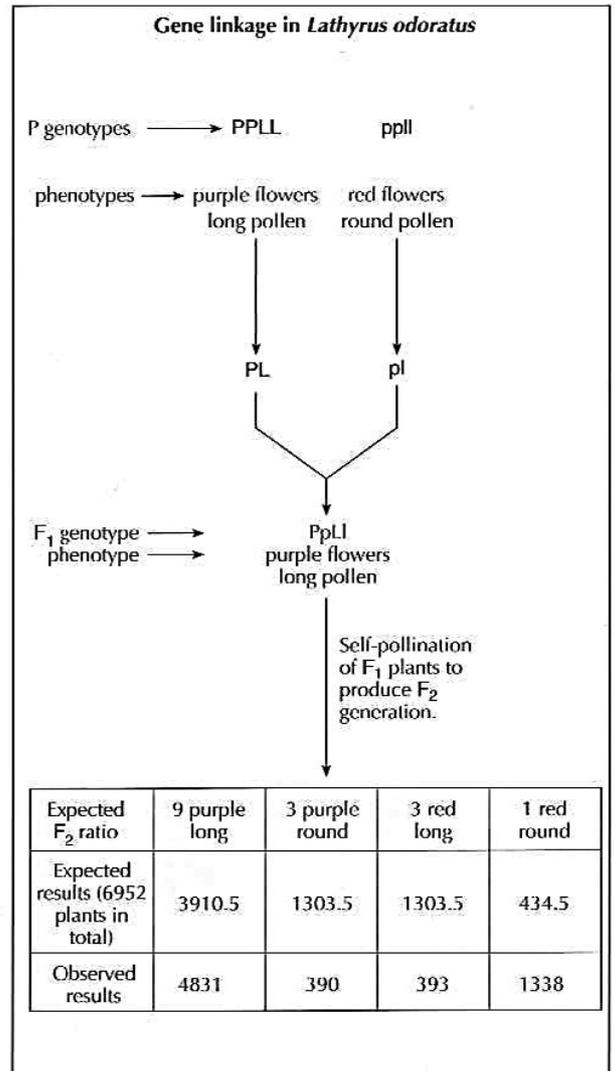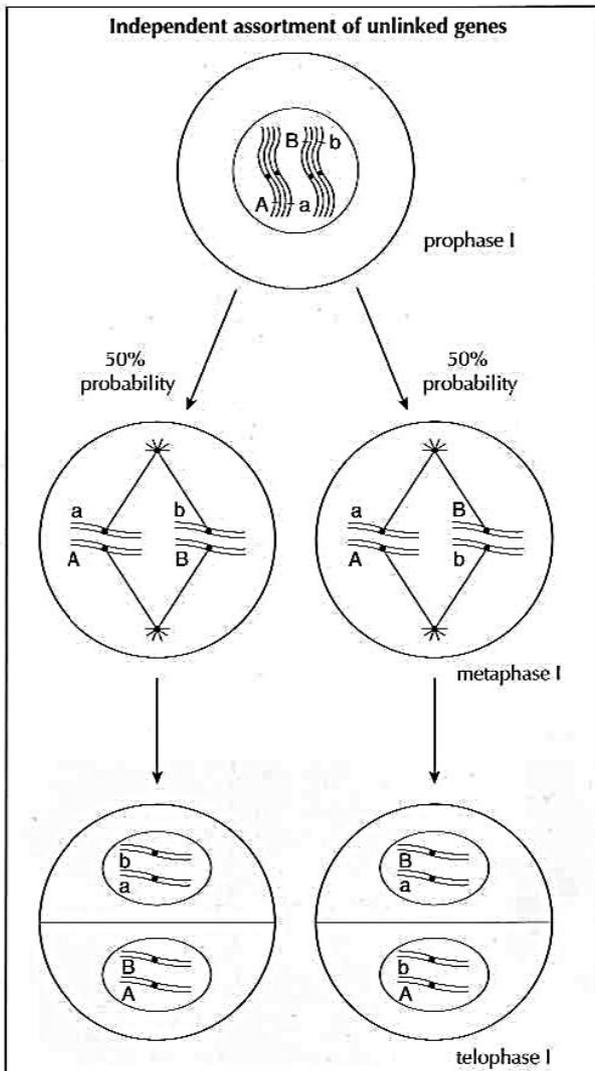
# Crossing-over

## EVENTS IN PROPHASE I OF MEIOSIS

Homologous chromosomes pair up in prophase I of meiosis. Each homologous chromosome consists of two sister chromatids. Chromatids of different chromosomes are called non-sister chromatids. While the chromosomes are paired, sections of chromatid are exchanged in a process called **crossing-over**.

The figure (right) shows how crossing-over occurs.

## BENEFITS OF CROSSING-OVER

Crossing-over has two important consequences.
1. It creates chiasmata which hold homologous chromosomes together in pairs called bivalents, during the later stages of prophase I and metaphase I until microtubules have attached.
2. It allows recombination of linked genes. All of the genes that have their loci on the same chromosome type form a **linkage group**.

Recombination of genes in a linkage group cannot occur without crossing-over. The point where crossing-over occurs along chromosomes is random – it can occur at a vast number of different points. Meiosis can therefore produce an almost infinite amount of genetic variety.

The figure (below) shows how crossing-over can cause recombination of linked genes. The figure (right) shows an example of a cross involving gene linkage, using bars to represent the chromosomes on which the genes are linked. A test cross was done on the $F_1$ plants.

### Recombination of linked genes

Parental gene combinations are AB and ab



Locus of gene A   Locus of gene B
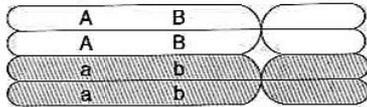
Crossing over occurs between the loci of the two genes

Position of chiasma formed by crossing over
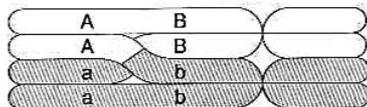
The four chromatids separate into the four nuclei produced by meiosis
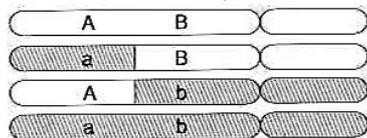
aB and Ab are recombinants

## The process of crossing over

At one stage in prophase I all of the chromatids of two homologous chromosomes become tightly paired up together. This is called *synapsis*.



four chromatids in total, long and thin at this stage

centromeres
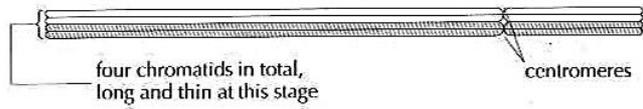
The DNA molecule of one of the chromatids is cut. A second cut is made at exactly the same point in the DNA of a non-sister chromatid.



DNA is cut at the same point in two non-sister chromatids
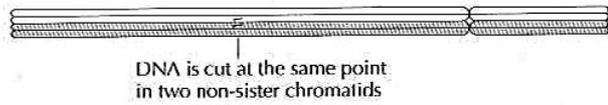
The DNA of each chromatid is joined up to the DNA of the non-sister chromatid. This has the effect of swapping sections of DNA between the chromatids.



In the later stages of prophase I the tight pairing of the homologous chromosomes ends, but the sister chromatids remain tightly connected. When each cross-over has occurred there is an X-shaped structure called a chiasma.



chiasma
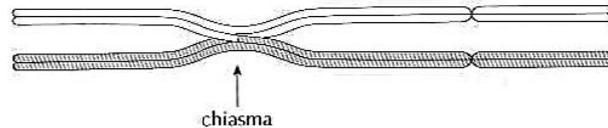
## AN EXAMPLE OF GENE LINKAGE AND TEST-CROSSING IN *ZEA MAYS*



| KEY | |
| --- | --- |
| C = allele for purple kernels | |
| c = allele for white kernels | |
| W = allele for starchy kernels | |
| w = allele for waxy kernels | |

Test cross using a plant that is homozygous recessive for both genes

| | purple starchy | purple waxy | white starchy | white waxy |
| --- | --- | --- | --- | --- |
| numbers | 147 | 65 | 58 | 133 |
| | Parental combination | Recombinants formed as a result of crossing over. | | Parental combination |
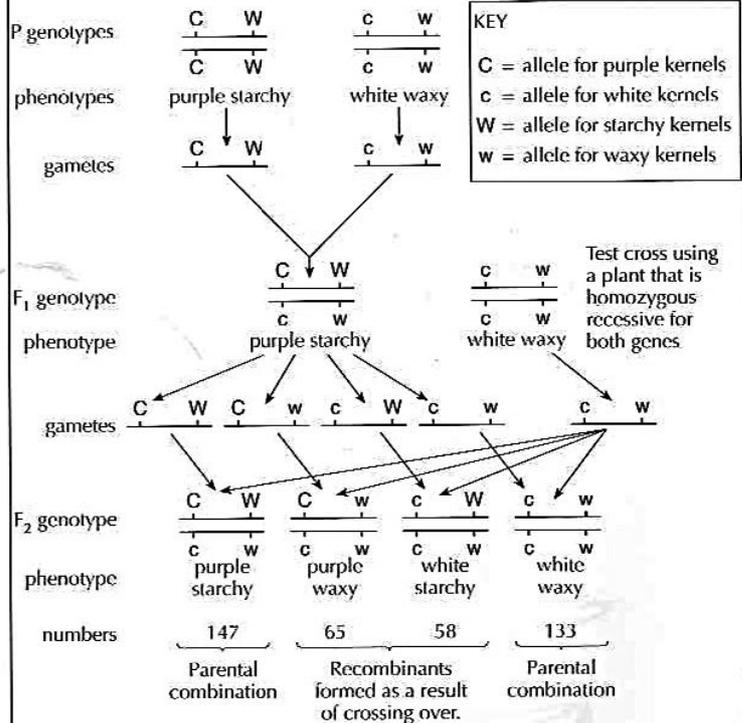
# Phases of meiosis

Meiosis involves two divisions. Each division is divided into four phases. The main events of each phase are listed below.

## PROPHASE I
- Chromosomes start to coil up and so become shorter and thicker.
- Homologous chromosomes pair up.
- Crossing over occurs.
- Centrioles move to the poles in animal cells.
- Nucleoli break down.
- At the end of prophase I the nuclear membrane breaks down.

## METAPHASE I
- Chromosomes continue to shorten and thicken.
- Spindle microtubules attach to the centromeres.
- Bivalents line up on the equator.
- Chiasmata slide towards the ends of the chromosomes, causing the shapes of the bivalents to change.
- At the end of metaphase I the chromosomes start to move.

## ANAPHASE I
- The two chromosomes of each bivalent move to opposite poles. This halves the chromosome number. Each chromosome consists of two chromatids. Because of crossing over the two chromatids are not identical.
- At the end of anaphase I the chromosomes reach the poles.

## TELOPHASE I
- Nuclear membranes form around the groups of chromosomes at each pole.
- The cell divides to form two haploid cells.
- The chromosomes uncoil partially.
- At the end of telophase I the two cells either enter a brief period of interphase or immediately proceed to the second division of meiosis. The DNA is not replicated.

## PROPHASE II
- Chromosomes become shorter and thicken again by coiling.
- Centrioles move to the poles in animal cells.
- At the end of prophase II the nuclear membranes break down.

## METAPHASE II
- Spindle microtubules attach to the centromeres.
- Chromosomes line up on the equator
- At the end of metaphase II the centromeres divide.

## ANAPHASE II
- The two chromatids of each chromosome move to opposite poles.
- At the end of anaphase II the chromatids reach the poles.

## TELOPHASE II
- Nuclear membranes form around the groups of chromatids at each pole. Each chromatid is now considered to be a chromosome.
- The two cells each divide to form to four cells in total.
- The chromosomes uncoil.
- Nucleoli appear.
- In most organisms the cells formed at the end of telophase II develop into gametes.

## SUMMARY OF MEIOSIS
1. Meiosis involves two divisions. One cell or nucleus divides to form four cells or nuclei.
2. The chromosome number is halved, from diploid to haploid.
3. An almost infinite amount of genetic variety is produced, as a result of crossing-over in prophase I and the random orientation of bivalents in metaphase I.

The figure (below) shows micrographs of four stages in meiosis in cells from the testis of a locust.



Early prophase I

Late prophase I

10 µm
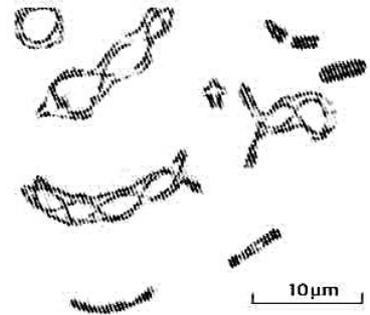
Anaphase I

Anaphase II

# EXAM QUESTIONS ON TOPIC 10

1  In some plants two genes control flower colour. [Note: – represents any allele]

   Plants with the genotype A_B_ have blue flowers.

   Plants with the genotype A_bb have red flowers.

   Plants with the genotype aa _ _ have white flowers.

   a) State the name given to the type of inheritance where more than one gene controls a single
      phenotypic characteristic.                                                              [1]

   A homozygous blue-flowered plant (AABB) is crossed with a homozygous white-flowered plant (aabb).

   b) State the genotype and phenotype of the $F_1$ offspring.                                [2]

   c) The $F_1$ plants are allowed to pollinate each other. Deduce, using the Punnett grid below, the genotypes of
      the gametes produced by the $F_1$ plants and the genotypes and phenotypes of all the possible $F_2$ offspring.  [5]

| gametes → | | | | |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |

   d) State the expected ratio of flower colours in the $F_2$ offspring.                     [1]

   e) The two genes code for enzymes used to convert a white substance into a red pigment and the red pigment
      into a blue pigment. Deduce the effect of the enzymes produced from gene A and gene B.  [1]

2  a) Define recombination.                                                                   [1]

   When grey bodied long winged Drosophila flies were test crossed with black bodied vestigial wing flies the $F_1$ generation
   was found to contain:

                    407 grey bodied long winged flies

                    396 black bodied vestigial winged flies

                    75 black bodied long winged flies

                    69 grey bodied vestigial winged flies

   b) Identify which of the flies were recombinants.                                          [2]

   c) The $F_1$ generation does not follow Mendel's Second Law (Law of Independent Assortment).
      Explain how the observed ratio could have arisen.                                       [3]

   d) Suggest how geneticists could make use of experimental results of the type shown above. [2]

3  The micrograph below shows a pair of homologous chromosomes in a cell carrying out meiosis in the grasshopper
   (*Chorthippus parallelus*).

   

   a) Identify the stage of meiosis of the cell that contained the pair of chromosomes.      [2]

   b) In the pair of chromosomes in the micrograph deduce the number of

      (i) chromatids                                                                          [1]

      (ii) chiasmata                                                                          [1]

   c) Outline how chiasmata are produced.                                                     [3]

# Antibody production

## STAGES IN ANTIBODY PRODUCTION

The production of antibodies by the immune system is one of the most remarkable biological processes. When a pathogen invades the body, the immune system gears up to produce large amounts of the specific antibodies needed to combat the pathogen. This process only takes a few days. The production of antibodies by B-cells is shown in a simplified form on page 50. Antibody production usually depends on other types of lymphocyte, including macrophages and helper T-cells. The roles of these cells are explained here.

### 1. Antigen presentation

Macrophages take in antigens by endocytosis, process them and then attach them to membrane proteins called MHC proteins. The MHC proteins carrying the antigens are then moved to the plasma membrane by exocytosis and the antigens are displayed on the surface of the macrophage. This is antigen presentation.



antigen is absorbed and then displayed by the macrophage

inactive helper T-cell

MHC protein

antigen presentation by macrophage
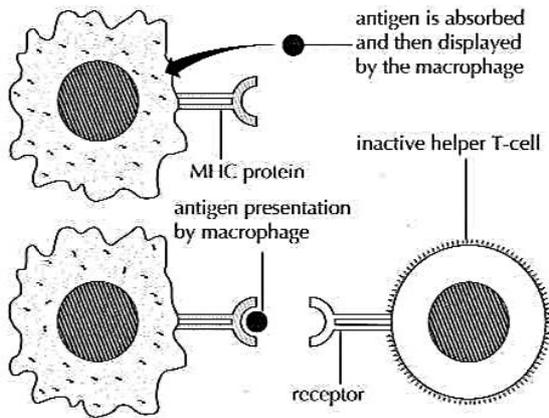
receptor

### 2. Activation of helper T-cells

Helper T-cells have receptors in their plasma membrane that can bind to antigens presented by macrophages. Each helper T-cell has receptors with the same antigen-binding domain as an antibody. These receptors allow a helper T-cell to recognize an antigen presented by a macrophage and bind to the macrophage. The macrophage passes a signal to the helper T-cell changing it from an inactive to an active state. This is activation of helper T-cells.



Helper T-cell binds to macrophage presenting the antigen

Macrophage sends a signal to activate the helper T-cell

activated helper T-cell
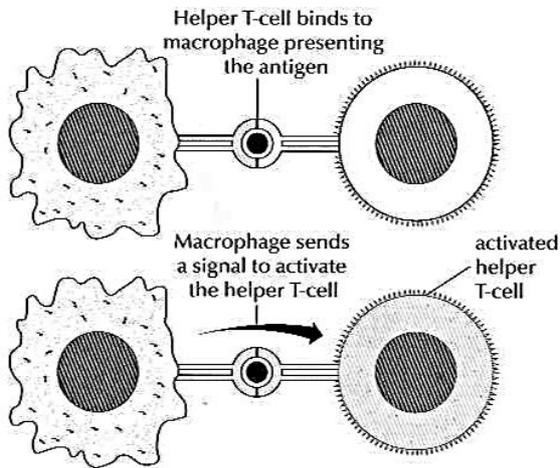
### 3. Activation of B-cells

Inactive B-cells have antibodies in their plasma membrane. If these antibodies match an antigen, the antigen binds to the antibody. An activated helper T-cell with receptors for the same antigen can then bind to the B-cell. The activated helper T-cell sends a signal to the B-cell, causing it to change from an inactive to an active state. This is activation of B-cells.



inactive B-cell

antigen binds to antibody in membrane of B-cell

antibody

Activated helper T-cell binds to B-cell

Activated helper T-cell sends a signal to activate the B-cell
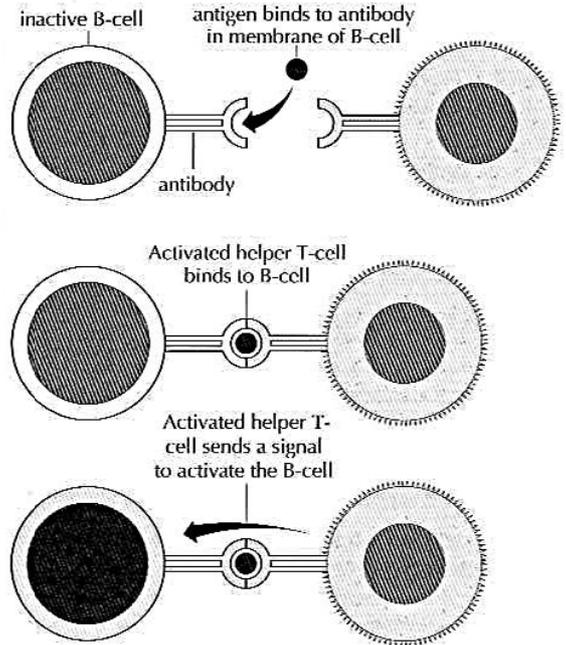
### 4. Production of plasma cells

Activated B-cells start to divide by mitosis to form a clone of cells. These cells become active, with a much greater volume of cytoplasm. They are then known as plasma cells. They have a very extensive network of rough endoplasmic reticulum. This is used for synthesis of large amounts of antibody, which is then secreted by exocytosis.



plasma cell
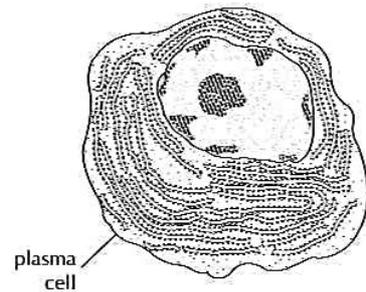
### 5. Production of memory cells

Memory cells are B-cells and T-cells that are formed at the same time as activated helper T-cells and B-cells, when a disease challenges the immune system. After the activated cells and the antibodies produced to fight the disease have disappeared, the memory cells persist and allow a rapid response if the disease is encountered again. Memory cells give long-term immunity to a disease.

# Immunity and vaccination

## ACTIVE AND PASSIVE IMMUNITY

Resistance to infection is called immunity. Antibodies give immunity to disease – this is sometimes called specific immunity, because one type of antibody gives protection against only one disease. Immunity can either be active or passive.

*Active immunity is due to production of antibodies by the organism itself after the body's defence mechanisms have been stimulated by antigens.*

An example is when infection with rubella virus causes immunity to rubella to develop and re-infection is very rare.

*Passive immunity is due to the acquisition of antibodies received from another organism, in which active immunity has been stimulated.*

Examples of passive immunity:
- During pregnancy, antibodies are passed across the placenta from mother to the fetus.
- The first milk produced after birth, called colostrum, contains antibodies that line the gut of newborn babies, helping to prevent infection.
- Antibodies are sometimes injected as an emergency treatment for virulent diseases, such as rabies.

## PRINCIPLES OF ANTIBODY PRODUCTION

The immune system has the potential to produce a vast range of different types of antibody – perhaps $10^{15}$ different types. It would be impossible to make large quantities of all of these antibodies. Instead, a few B-cells that can make a type of antibody are produced and if these cells encounter an antigen to which their antibody binds, they multiply to form a clone of many cells. This is called **clonal selection**.

Sometimes several different types of antibody can bind to the same antigen, so more than one clone of cells is formed. This is called polyclonal selection.

A clone of B-cells can produce large amounts of antibody quickly and so give immunity to the disease with which the antigen is associated. Immunity to a disease is only developed if the disease challenges the immune system. This is called the principle of **challenge and response**.

These two principles do not fully explain antibody diversity. Research is ongoing into two additional processes:
- how lymphocytes splice together DNA taken from various parts of the genome, to produce a huge variety of genes coding for antibodies
- how rapid mutation occurs in antibody genes in lymphocytes that have been activated by antigen binding – this gives the chance of producing antibodies that fit the antigen better.

## VACCINATION

A vaccine is a modified form of a disease-causing microorganism that stimulates the body to develop immunity to the disease, without fully developing the disease. Vaccines contain weakened forms of the microorganisms, killed forms or chemicals produced by the microorganism that act as antigens. The vaccine is either injected into the body or sometimes swallowed. The principle of vaccination is that antigens in the vaccine cause the production of the antibodies needed to control the disease. Sometimes two or more vaccinations are needed to stimulate the production of enough antibodies. The figure (right) shows a typical response to a first and second vaccination against a disease. The first vaccination causes a little antibody production and the production of some memory cells. The second vaccination, sometimes called a booster shot, causes a response from the memory cells and therefore faster and greater production of antibodies. Memory cells should persist to give long-term immunity.

**Response to first and second vaccinations**
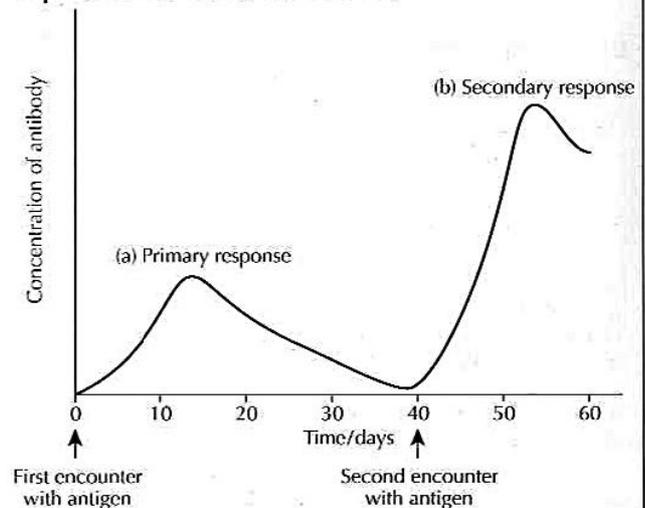


## VACCINATION – BENEFITS AND DANGERS

There are huge benefits from vaccination:
1. Epidemics and pandemics can be prevented and some diseases can be completely eradicated – smallpox was the first and polio may be the second.
2. Deaths due to disease can be prevented. For example, measles is a major cause of death of unvaccinated children in some parts of the world.
3. Disability due to disease can be prevented, decreasing health care costs, for example deafness and blindness in babies whose mothers were not vaccinated and so contracted rubella during pregnancy.

Immunization is the most effective of all public health interventions. All vaccines are very carefully tested before being introduced and the risks of the diseases that they prevent are much greater than any adverse effects associated with vaccines themselves.

Unfortunately, the diseases that vaccines prevent become rare so that parents worry more about the vaccine than the disease. As a result unfounded stories of the dangers of vaccines easily tip public opinion against vaccination, with very serious consequences for child health.

Serious adverse reactions which are caused by vaccines, such as severe allergic reactions (anaphylaxis), are very rare. Most other vaccine reactions are minor and recover without treatment: fever, or pain, swelling and redness at the site of vaccination.

# Monoclonal antibodies and blood clotting

## PRODUCTION OF MONOCLONAL ANTIBODIES

Large quantities of a single type of antibody can be made using an ingenious technique.

- Antigens that correspond to a desired antibody are injected into an animal.
- B-cells producing the desired antibody are extracted from the animal.
- Tumour cells are obtained. These cells grow and divide endlessly.
- The B-cells are fused with the tumour cells, producing hybridoma cells that divide endlessly and produce the desired antibody.
- The hybridoma cells are cultured and the antibodies that they produce are extracted and purified.

The figure (right) shows a factory used for the industrial production of monoclonal antibodies. There are many ways in which monoclonal antibodies can be used. Two examples are described here.

### Treatment of anthrax

Anthrax is a disease caused by a bacterium that produces toxins. It is often lethal, even when antibiotic treatments are given. Anthrax spores have sometimes been used deliberately to infect people and cause death.
Monoclonal antibodies are being developed which neutralize one of the toxins and therefore sustain the patient's life until their immune system produces antibodies naturally.



### Diagnosis of malaria

Tests using monoclonal antibodies have been developed for many diseases, including malaria. Monoclonal antibodies are produced that bind to antigens in malarial parasites. A test plate is coated with the antibodies. A sample is left in the plate long enough for malaria antigens in the sample to bind to the antibodies. The sample is then rinsed off the plate. Any bound antigens are detected using more monoclonal antibodies with enzymes attached that cause a colour change. This is called an ELISA test. It can be used to measure the level of infection and to distinguish between different strains of malaria, either in humans or in mosquitoes.

## BLOOD CLOTTING

When human tissue is injured and blood escapes from blood vessels, a semi-solid is formed from liquid blood to seal up the wound and prevent entry of pathogens. The semi-solid is called a **blood clot** and the process is called **clotting**.

Platelets have an important role in clotting. Platelets are small cell fragments that circulate with erythrocytes and leukocytes in the blood plasma. The clotting process begins with the release of clotting factors either from damaged tissue cells or from platelets. These clotting factors set off a series of reactions in which the product of each reaction is the catalyst of the next reaction. This system helps to ensure that clotting only happens when it is needed and it also makes it a very rapid process. In the last reaction fibrinogen, a soluble plasma protein is altered by the removal of sections of peptide that have many negative charges. This allows the remaining polypeptide to bind to others, forming long protein fibres called fibrin. Fibrin forms a mesh of fibres across wounds. Blood cells are caught in the mesh and soon form a semi-solid clot. If exposed to air the clot dries to form a protective scab, which remains until the wound has healed.

### Final reactions in blood clotting
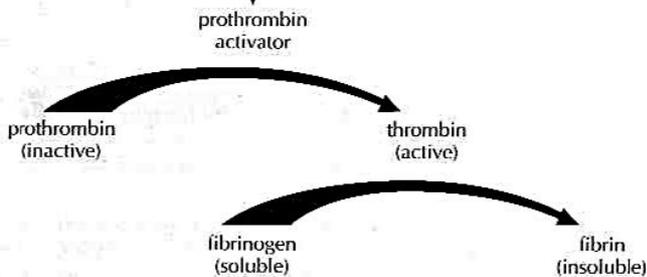


### Fibrin and blood cells in a blood clot
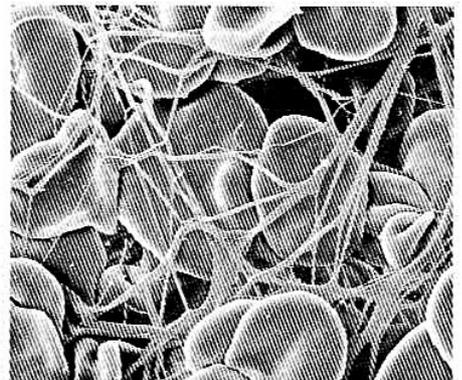
# Muscles and joints

## MOVEMENT IN HUMANS

The muscular-skeletal system and nervous system are responsible for movement in humans.

- **Muscles** provide the force needed for muscle contraction. They do this when they contract.
- **Tendons** attach muscles to bone.
- **Bones** provide a firm anchorage for muscles. They also act as levers, changing the size or direction of forces generated by muscles.
- **Ligaments** connect bone to bone, restricting movement at joints and helping to prevent dislocation.
- **Nerves** stimulate muscles to contract at a precise time and extent, so that movement is co-ordinated.

## JOINTS

Junctions between bones are called joints.

- **Cartilage** reduces friction between bones where they meet.
- **Synovial fluid** lubricates the joint to reduce friction.
- **Joint capsule** seals the joint and holds in the synovial fluid.

The knee is a hinge joint. It allows considerable movement in one plane: bending (flexion) or straightening (extension), but little movement in the other two planes. In contrast, the hip joint allows movement in three planes (protraction /retraction, abduction/adduction and rotation). The figure (below) shows the structure of the elbow joint.

## THE ELBOW JOINT

biceps – the flexor muscle, used to bend the arm at the elbow

tendon – attaches muscle to bone

capsule sealing the joint

tendon of triceps

tendon of biceps

ligaments – tough cords of tissue linking bone to bone, to prevent dislocation

humerus bone – provides a firm anchorage for the muscles

triceps – the extensor muscles, used to straighten the arm

capsule – seals the joint

synovial fluid – lubricates the joint to reduce friction

radius – bone that transmits forces from the biceps through the forearm

ulna – bone that transmits forces from the triceps through the forearm

cartilage – a layer of smooth and tough tissue that covers the ends of the bones where they meet to reduce friction

## STRUCTURE OF STRIATED MUSCLE FIBRES

When viewed with a light microscope skeletal muscle is seen to consist of large multinucleate cells called **muscle fibres**. Within each muscle fibre are cylindrical structures called **myofibrils**. The myofibrils consist of repeating units called **sarcomeres**, which have light and dark bands. The light and dark bands extend across all the myofibrils in a muscle fibre, giving it a striated (striped) appearance. Around each myofibril is a special type of endoplasmic reticulum, called sarcoplasmic reticulum, visible in the electron micrograph (right). There are also mitochondria between the myofibrils.

nucleus

sarcolemma (membrane of muscle fibre)

myofibrils

nucleus

dark bands

light bands
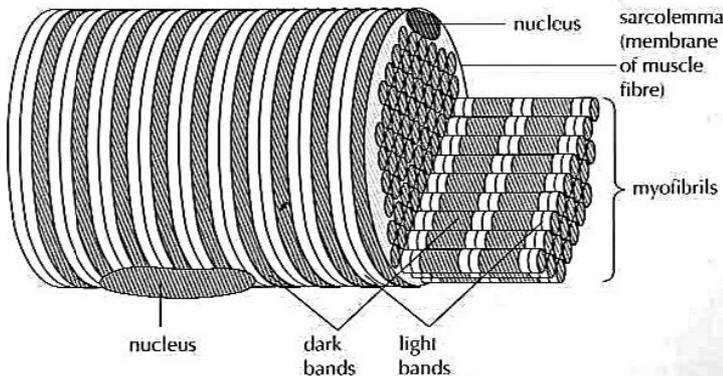
# Muscle contraction

## STRUCTURE OF A SARCOMERE

A sarcomere is a subunit of a myofibril. At either end is a Z line to which narrow actin filaments are attached. The actin filaments stretch inwards towards the centre of the sarcomere. Between them, there are thicker myosin filaments, which have heads that can bind to the actin. The part of the sarcomere containing myosin is the dark band and the part containing only actin filament is the light band. The figure (right) shows the structure of a sarcomere.

thick myosin filaments

thin actin filaments

Z line

light band    dark band

one sarcomere
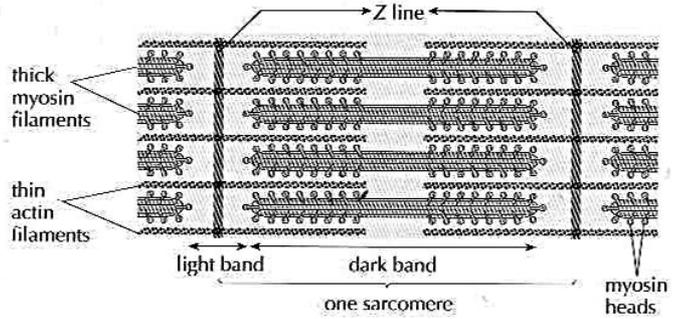
myosin heads

## CONTRACTION OF SKELETAL MUSCLE

When a motor neurone stimulates a striated muscle fibre, calcium ions are released from the sarcoplasmic reticulum. The calcium causes binding sites on actin to be revealed, allowing myosin heads to bind. A cycle of events occurs, which causes actin filaments to slide inwards towards the centre of the sarcomeres. This makes the light bands narrower and the sarcomeres shorter – the muscle fibre contracts. The figure (below) shows the events that cause muscle contraction. The electron micrographs show striated muscle in relaxed (bottom left) and contracted (bottom right) states.

① Myosin filaments have heads which form cross-bridges when they are attached to binding sites on actin filaments.

② ATP binds to the myosin heads and causes them to break the cross-bridges by detaching from the binding sites.

MOVEMENT

ADP + P

ATP

⑤ The ADP and phosphate are released and the heads push the actin filament inwards towards the centre of the sarcomere. This is called the power stroke.

ADP + P

③ ATP is hydrolysed to ADP and phosphate, causing the myosin heads to change their angle. The heads are said to be 'cocked' in their new position as they are storing potential energy from ATP.

ADP + P

④ The heads attach to binding sites on actin that are further from the centre of the sarcomere than the previous sites.

**Relaxed muscle**

**Contracted muscle**
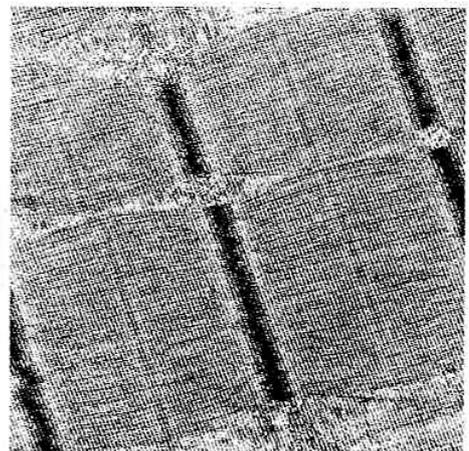
# Kidney structure and ultrafiltration

## FUNCTIONS OF THE KIDNEY

The kidney has two functions – excretion and osmoregulation.

*Excretion is the removal from the body of the waste products of metabolic pathways.*

*Osmoregulation is the control of the water balance of the blood, tissue or cytoplasm of a living organism.*

## THE STRUCTURE OF THE KIDNEY

The kidneys produce urine. The figure (below) shows the structure of the kidney. The cortex and medulla of the kidney contain many narrow tubes called nephrons. The figure (below) shows the structure of a nephron, together with the associated glomerulus.

**Structure of a kidney in vertical section**
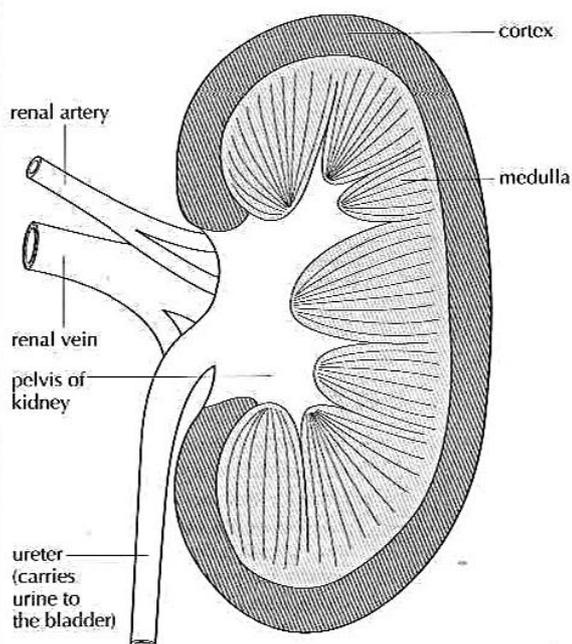


**Structure of part of a glomerulus**
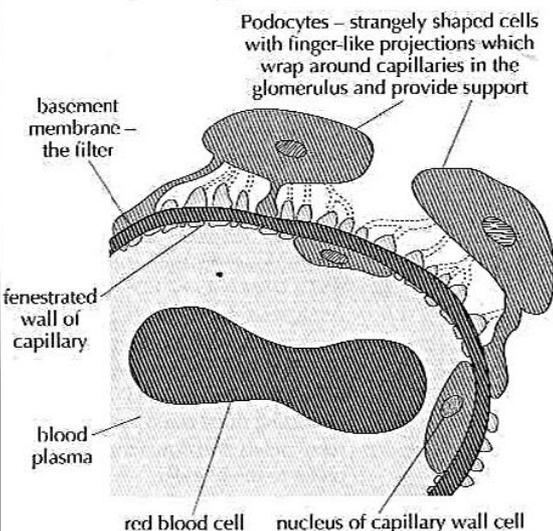


## ULTRAFILTRATION IN THE GLOMERULUS

The function of the glomerulus is production of a filtrate from blood by a process called **ultrafiltration**. Part of the blood plasma escapes through the walls of all capillaries, but in the glomerulus 20% escapes, which is much greater than usual. There are two main reasons for this.

- The blood pressure is very high, because the vessel taking blood away from the glomerulus is narrower than the vessel bringing blood.
- The capillaries in the glomerulus are fenestrated – they have many pores through them.

These pores are large enough to allow any molecules through, but on the outside of the capillary wall is a basement membrane, composed of a gel of glycoproteins (below). The basement membrane acts as a filter as it only allows molecules with a molecular mass below 68 000 to pass through. It lets all substances in blood plasma through except plasma proteins. The fluid produced by ultrafiltration is collected by the Bowman's capsule and flows on into the proximal convoluted tubule.

**Structure of the nephron**
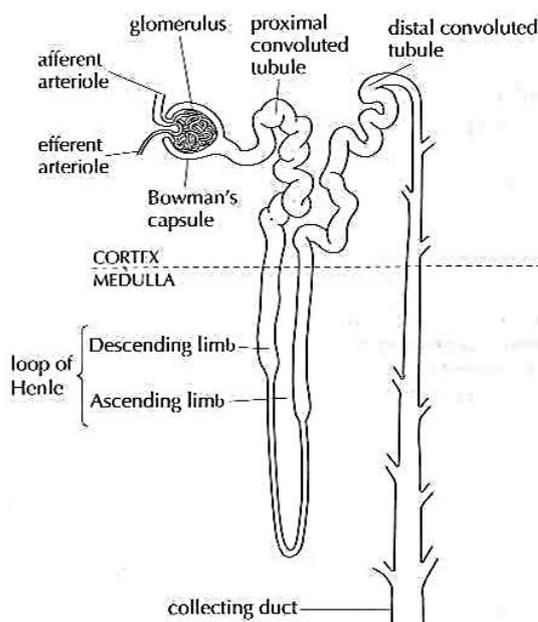


## COMPARISON OF FLUIDS IN THE KIDNEY

The physiology of the kidney can be studied by comparing the content of blood flowing to and from the kidney with the content of glomerular filtrate and urine.

**Content (mg per 100ml of blood)**

|  | Blood in renal artery | Urine | Glomerular filtrate | Blood in renal vein |
|---|---|---|---|---|
| **Glucose** | 90 | 0 | 90 | 90 |
| **Urea** | 30 | 2000 | 30 | 24 |
| **Proteins** | 740 | 0 | 0 | 740 |

Glucose is often present in the urine of untreated diabetic patients. This is because the glucose concentration of blood rises much higher than 90 mg per 100 ml, so the pumps in the proximal convoluted tubule cannot reabsorb all the glucose that is filtered out in the glomerulus.

# Urine production and osmoregulation

## SELECTIVE RE-ABSORPTION IN THE PROXIMAL CONVOLUTED TUBULE

Large volumes of glomerular filtrate are produced – about 1 litre every 10 minutes by the two kidneys. As well as waste products, the filtrate contains substances that the body needs, which must be re-absorbed into the blood. Most of this **selective re-absorption** happens in the proximal convoluted tubule. The wall of the nephron consists of a single layer of cells. In the proximal convoluted tubule the cells have microvilli projecting into the lumen (right), giving a large surface area for absorption. Pumps in the membrane re-absorb useful substances by active transport, using ATP produced by mitochondria in the cells. All of the glucose in the filtrate is re-absorbed. About 80% of the mineral ions, including sodium is re-absorbed. Active transport of solutes makes the total solute concentration higher in the cells of the wall than in the filtrate in the tubule. Water therefore moves from the filtrate to the cells and on into the adjacent blood capillary by osmosis. About 80% of the water in the filtrate is re-absorbed, leaving 20% of the original volume to flow on into the loop of Henle.

### Structure of the proximal convoluted tubule



microvilli — mitochondria — invaginations of outer membrane — basement membrane — lumen containing filtrate
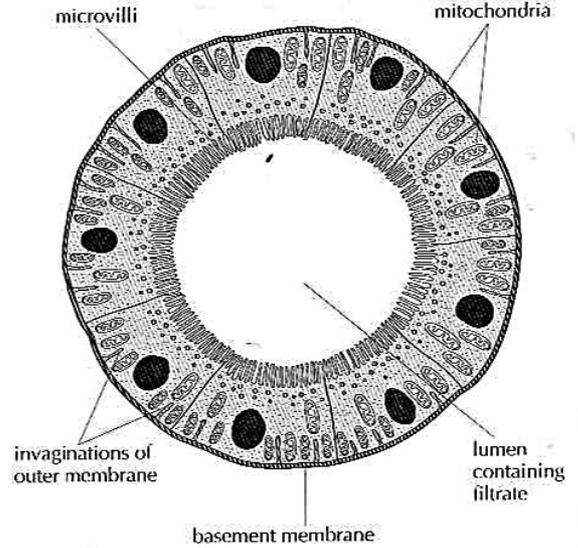
## THE ROLE OF THE LOOP OF HENLE

Glomerular filtrate flows deep into the medulla in descending limbs of the loops of Henle and then back out to the cortex in ascending limbs. Descending limbs and ascending limbs are opposite in terms of permeability. Descending limbs are permeable to water but not to sodium ions. Ascending limbs are permeable to sodium ions but not to water (right). Ascending limbs pump sodium ions from the filtrate into the medulla by active transport, creating a high solute concentration in the medulla. As the filtrate flows down the descending limb into this region of high solute concentration, some water is drawn out by osmosis. This dilutes the fluids in the medulla slightly. However the filtrate that leaves the loop of Henle is more dilute than the fluid entering it, showing that the overall effect of the loop of Henle is to increase the solute concentration of the medulla. This is the role of the loop of Henle – to create an area of high solute concentration in the cells and tissue fluid of the medulla. After the loop of Henle, the filtrate passes through the distal convoluted tubule, where the ions can be exchanged between the filtrate and the blood to adjust blood levels. It then passes into the collecting duct.
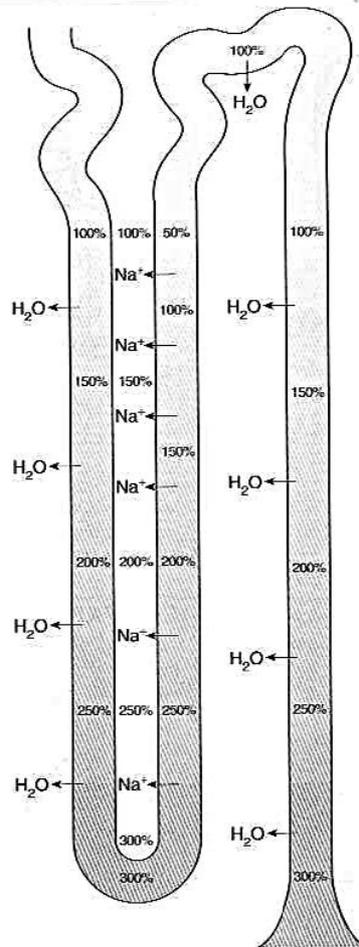


**Movements of water and sodium ions in the loop of Henle and the collecting duct.** Solute concentrations inside and outside the nephron are shown as a percentage of normal blood solute concentration

## OSMOREGULATION IN THE COLLECTING DUCT

Osmoregulation is the control of water and solute levels. The collecting duct has an important role in osmoregulation. If the water content of the blood is too low, the pituitary gland secretes ADH. This hormone makes the cells of the collecting duct produce membrane channels called aquaporins, which makes the collecting duct permeable to water. As the filtrate passes down the collecting duct through the medulla, the high solute concentration of the medulla causes most of the water in the filtrate to be re-absorbed by osmosis. A small volume of concentrated urine is produced.

If the water content of the blood is too high, ADH is not secreted, aquaporins are broken down and the collecting duct becomes much less permeable to water. Little water is reabsorbed as the filtrate passes down the collecting duct and a large volume of dilute urine is produced. In this way the water content of the blood is kept within narrow limits. The urine produced by the collecting ducts drains into the renal pelvis and down the ureter to the bladder.

# Spermatogenesis

Spermatogenesis is the production of spermatozoa. Spermatozoa are usually simply called sperm. Spermatogenesis occurs in the testes, in narrow tubes called **seminiferous tubules**.

The figures (below and right) show the structure of testis tissue, including the seminiferous tubules. The figure (bottom) shows the processes involved in spermatogenesis.

## Structure of testis tissue

wall of seminiferous tubule

fluid inside seminiferous tubule

blood vessel

interstitial cells (Leydig cells) secrete testosterone
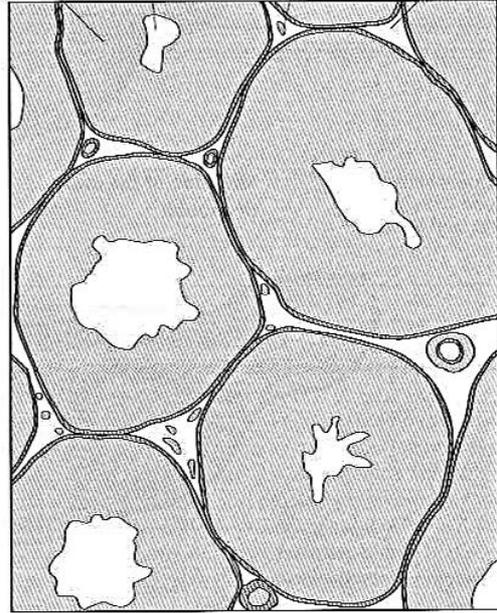


### Micrograph of testis tissue (× 90)
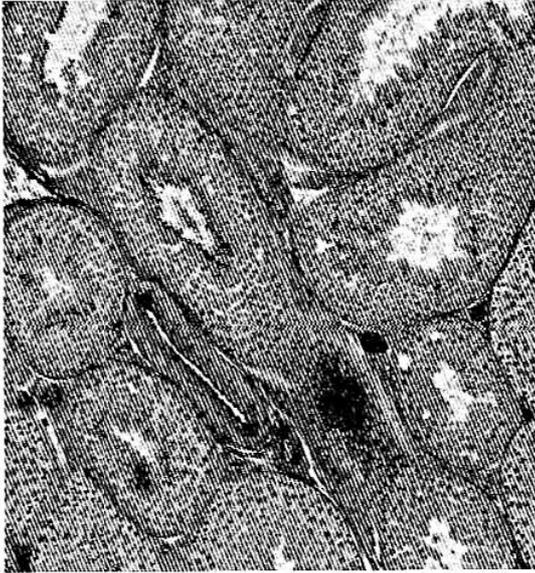


## STAGES OF SPERMATOGENESIS



basement membrane

spermatogonium

① An outer layer called germinal epithelium cells (2n) divide endlessly by **mitosis** to produce more diploid cells.

② Diploid cells **grow** larger and are then called *primary spermatocytes* (2n)

primary spermatocyte

③ Each primary spermatocyte carries out the **first division of meiosis** to produce two *secondary spermatocytes* (n).

secondary spermatocyte

④ Each secondary spermatocyte carries out the **second division of meiosis** to produce two *spermatids* (n).

⑥ Sperm detach from Sertoli cells and eventually are carried out of the testis by the fluid in the centre of the seminiferous tubule.

spermatids

⑤ Spermatids become associated with nurse cells, called Sertoli cells, which help the spermatids to develop into *spermatozoa* (n). This is an example of **cell differentiation**.

# Oogenesis

Oogenesis is the production of an ovum. Ova are often simply called eggs. Oogenesis occurs in the ovaries.
The figures below show the structure of ovary tissue.
The figure (bottom) shows the processes involved in oogenesis.

**Micrograph of the ovary of a rabbit**



**Structure of the ovary of a rabbit**
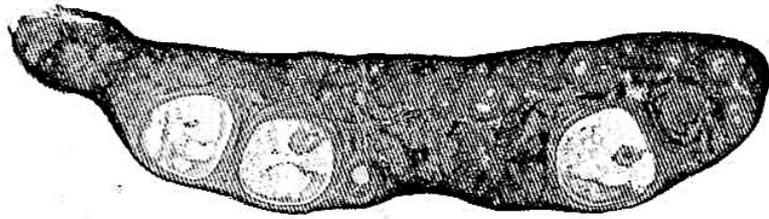


region where blood vessels enter and leave

medulla (containing blood vessels)

outer layer of germinal epithelium cells

cortex (containing primary follicles)

secondary oocyte inside a mature follicle

## STAGES OF OOGENESIS

③ Primary oocytes start the **first division of meiosis** but stop during prophase I. The primary oocyte and a single layer of follicle cells around form a primary follicle.

④ When a baby girl is born the ovaries contain about 400 000 primary follicles.

⑤ Every menstrual cycle a few primary follicles start to develop. The primary oocyte completes the first division of meiosis, forming two haploid nuclei. The cytoplasm of the primary oocyte is **divided unequally** forming a large secondary oocyte ($n$) and a small polar cell ($n$).

② Diploid cells **grow** into larger cells called primary oocytes ($2n$).

① In the ovaries of a female fetus, germinal epithelium cells ($2n$) divide by **mitosis** to form more diploid cells ($2n$).



developing follicles

primary follicles

primary oocyte

single layer of follicle cells

first polar cell

secondary oocyte

flap of tissue connecting ovary to abdomen

corpus luteum (develops from the follicle after ovulation)

egg released at ovulation

three layers of follicle cells

secondary oocyte in prophase II

follicular fluid

mature follicle

⑥ The secondary oocyte starts the **second division of meiosis** but stops in prophase II. The follicle cells meanwhile are proliferating and follicular fluid is forming.

⑧ After fertilization the secondary oocyte completes the second division of meiosis to form an ovum, (with a sperm nucleus already inside it) and a second polar cell or body. The first and second polar bodies do not develop and eventually **degenerate.**

⑦ When the mature follicle bursts, at the time of ovulation, the egg that is released is actually still a secondary oocyte.

# Gametes

## STRUCTURE OF HUMAN SPERM



head (3 μm wide and 4μm long)

acrosome

haploid nucleus

mid-piece (7μm long)

tail (40μm long, two-thirds of it omitted from this drawing)

plasma membrane

centriole

helical mitochondria

microtubules in a 9+2 arrangement

protein fibres to strengthen the tail
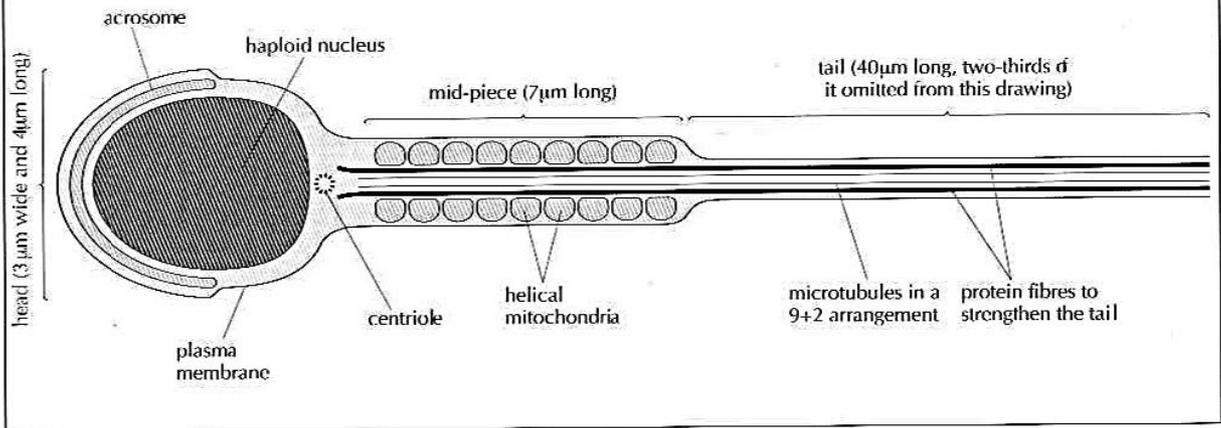
## HORMONAL CONTROL OF SPERMATOGENESIS

Three hormones are involved in the production of sperm.

| Hormone | Source | Role |
|---------|--------|------|
| FSH | Pituitary gland | Stimulates primary spermatocytes to undergo the first division of meiosis, to form secondary spermatocytes |
| Testosterone | Interstitial cells in the testis | Stimulates the development of secondary spermatocytes into mature sperm |
| LH | Pituitary gland | Stimulates the secretion of testosterone by the testis |

## PRODUCTION OF SEMEN

Three structures help to produce semen – the epididymis, seminal vesicles and prostate gland
When sperm from the testis arrive in the epididymis, they are unable to swim. The sperm undergo a maturing process while they are stored in the epididymis and become able to swim. The two seminal vesicles and prostate gland produce and store fluids and expel them during ejaculation. The fluid mixes with the sperm and increases the volume of the ejaculate. The fluid from the seminal vesicles contains nutrients for the sperm including fructose. It also contains mucus which protects the sperm in the vagina. The fluid from the prostate gland contains mineral ions and is alkaline so protects the sperm from the acid conditions in the vagina.

## STRUCTURE OF A HUMAN EGG



haploid nucleus

cytoplasm (or yolk) containing droplets of fat

two centrioles

first polar cell

plasma membrane

cortical granules

layer of follicle cells (corona radiata)

layer of gel composed of glycoproteins (zona pellucida)

Diameter of egg cell = 110 μm
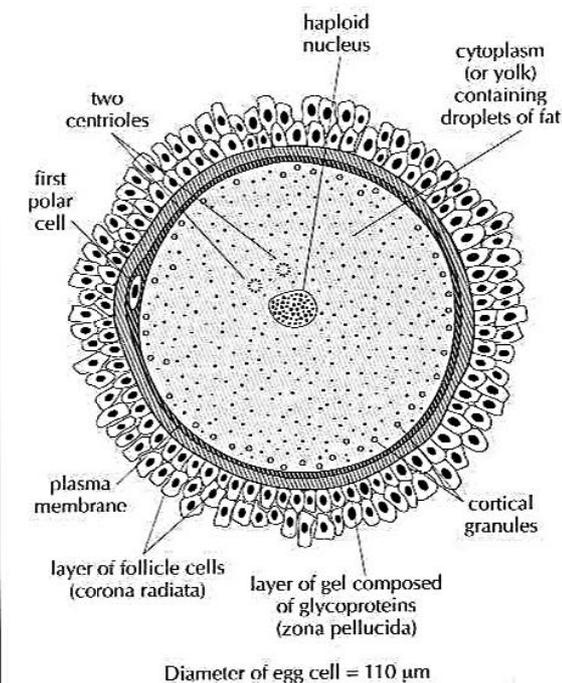
## COMPARING SPERMATOGENESIS WITH OOGENESIS

There are many similarities between the formation of sperm and eggs.
• Both start with proliferation of cells by mitosis.
• Both involve the cell growth before meiosis.
• Both involve the two divisions of meiosis.

The table below shows some of the differences.

| Spermatogenesis | Oogenesis |
|-----------------|-----------|
| Millions produced daily | One produced every 28 days |
| Released during ejaculation | Released on about day 14 of menstrual cycle by ovulation |
| Sperm formation starts during puberty in boys | The early stages of egg production happen during fetal development in females |
| Sperm production continues throughout the adult life of men | Egg production becomes irregular and then stops at the menopause in women |
| Four sperm are produced per meiosis | Only one egg is produced per meiosis |

# Fertilization

## Summary of spermatogenesis



germinal epithelium cells

mitosis

cell growth

primary spermatocyte — 2n

1st division of meiosis

secondary spermatocyte — n, n

2nd division of meiosis

spermatids — n, n, n, n

cell differentiation

spermatozoa — n, n, n, n

## Summary of oogenesis



germinal epithelium cells

mitosis

cell growth

primary oocyte — 2n

1st division of meiosis

secondary oocyte and first polar body — n

2nd division of meiosis

ovum and second polar body — n

## Stages in the fertilization of a human egg



sperm try to push through the layers of follicle cells around the egg
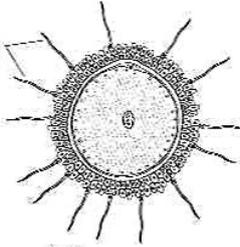
### 1. Arrival of sperm
Sperm are attracted by a chemical signal and swim up the oviduct to reach the egg. Fertilization is only successful if many sperm reach the egg.



follicle cell

zona pellucida

plasma membrane of egg

### 2. Binding
The first sperm to break through the layers of follicle cells binds to the zona pellucida. This triggers the acrosome reaction.



acrosomal cap

### 3. Acrosome reaction
The contents of the acrosome are released, by the separation of the acrosomal cap from the sperm. Proteases from the acrosome digest a route for the sperm through the zona pellucida, allowing the sperm to reach the plasma membrane of the egg.



tail and mitochondria usually remain outside

cortical granules

### 4. Fusion
The plasma membranes of the sperm and egg fuse and the sperm nucleus enters the egg and joins the egg nucleus. Fusion causes the cortical reaction.



hardened zona pellucida

exocytosis of contents of cortical granules

sperm nucleus

### 5. Cortical reaction
Small vesicles called cortical granules move to the plasma membrane of the egg and fuse with it, releasing their contents by exocytosis. Enzymes from the cortical granules cause cross-linking of glycoproteins in the zona pellucida, making it hard and preventing the entry of any more sperm.



two polar cells

two haploid nuclei from the sperm and the egg

### 6. Mitosis
The nuclei from the sperm and egg do not fuse together. Instead, both nuclei carry out mitosis, using the same centrioles and spindle of microtubules. A two-cell embryo is produced.

# Pregnancy and childbirth

## FERTILIZATION AND EARLY EMBRYO DEVELOPMENT

If a couple want to have a child, they have sexual intercourse without using any method of contraception. The biological term for sexual intercourse is **copulation**. During copulation, semen is ejaculated into the vagina. Sperm swim through the cervix, up the uterus and into the oviducts. If there is an egg in the oviducts, a sperm can fuse with it to produce a zygote. The fusion of an egg with a sperm is called **fertilization**.

The zygote produced by fertilization in the oviduct is a new human individual. It starts to divide by mitosis to form a 2-cell embryo, then a 4-cell embryo (right) and so on until a hollow ball of cells called a blastocyst is formed. While these early stages in the development of the embryo are happening, the embryo is transported down the oviduct to the uterus. When it is about 7 days old, the embryo implants itself into the wall of the uterus, where it continues to grow and develop.



4-cell embryo

## DEVELOPMENT OF THE FETUS

By the time that embryo is about 8 weeks old, it starts to develop bone tissue and is known from then onwards as a **fetus**. The fetus develops a placenta and an umbilical cord (left). The placenta is a disc-shaped structure, with many projections called placental villi embedded in the uterus wall. In the placenta the blood of the fetus flows close to the blood of the mother in the uterus wall. Materials are exchanges between maternal and fetal blood. For example, oxygen passes from maternal to fetal blood and carbon dioxide passes from fetal to maternal blood. The fetus also develops around itself an amniotic sac containing amniotic fluid. The fetus floats in this amniotic fluid and is supported by it. The delicate tissues of the fetus are protected from injury by the amniotic fluid, which acts as a shock absorber. This is needed if an everyday event or an accident causes an impact to the mother's abdomen.

A sample of fluid can be taken from the amniotic sac by inserting a hypodermic needle through the abdomen wall. This procedure is known as **amniocentesis**. The fluid contains fetal cells which can be cultured to make them divide. The chromosomes of the dividing cells can be examined to test for chromosomal abnormalities such as Down's syndrome.



Female reproductive system during pregnancy

- amniotic sac
- developing fetus
- uterus wall
- vagina
- amniotic fluid
- placenta
- umbilical cord
- cervix

## CHILDBIRTH

Through the 9 months of pregnancy, the hormone progesterone ensures that the uterus develops and sustains the growing fetus. The level of progesterone in the mother becomes increasingly high. The end of pregnancy is signalled by a fall in progesterone level. This allows the mother's body to secrete another hormone – oxytocin. Oxytocin causes the muscle in the uterus wall to contract. Uterine contractions stimulate the secretion of more oxytocin. The uterine contractions therefore become stronger and stronger. This is an example of **positive feedback**.

While the muscle in the wall of the uterus is contracting, the cervix relaxes and becomes wider. The amniotic sac bursts and the amniotic fluid is released. Finally, often after many hours of contractions, the baby is pushed out through the cervix and the vagina. The umbilical cord is cut and the baby begins its independent life. Contractions continue for a time until the placenta is expelled as the afterbirth.



Childbirth almost completed

- uterus wall contracting
- vagina – the birth canal
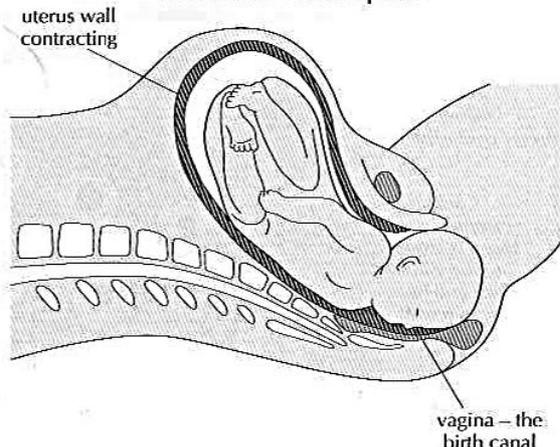
# Structure and function of the placenta

## HORMONAL CONTROL OF PREGNANCY

Estrogen and progesterone are needed throughout pregnancy to stimulate the development of the uterus lining. During the first few days after ovulation the corpus luteum secretes these hormones whether or not there has been fertilization. After implanting in the uterus wall, the embryo starts to secrete a hormone called HCG (human chorionic gonadotrophin). HCG prevents degeneration of the corpus luteum, which would happen at the end of a menstrual cycle. HCG stimulates the corpus luteum to grow and to continue secretion of estrogen and progesterone. This is essential to allow the pregnancy to continue. By the middle of the pregnancy, the corpus luteum starts to degenerate, but by then cells in the placenta are secreting estrogen and progesterone and these cells secrete increasing amounts until the end of the pregnancy.

## STRUCTURE AND FUNCTION OF THE PLACENTA

The figure (below) shows the structure and functions of the placenta.
The figure (bottom) shows how materials are exchanged between maternal and fetal blood at the surface of villi in the placenta.

### Structure of the placenta



Placenta – a disc-shaped structure, 185 mm in diameter and 20 mm thick when fully grown.

Placental villi – small projections that give a large surface area (14m²) for gas exchange and exchange of other materials. Fetal blood flows through capillaries in the villi.

Inter-villous spaces – maternal blood flows through these spaces, brought by uterine arteries and carried away by uterine veins.

Deoxygenated fetal blood flows from the fetus to the placenta along two umbilical arteries.

Oxygenated fetal blood flows back to the fetus from the placenta along the umbilical vein.

Endometrium – the lining of the uterus, into which the placenta grows.

Myometrium – muscular wall of the uterus, used during childbirth.
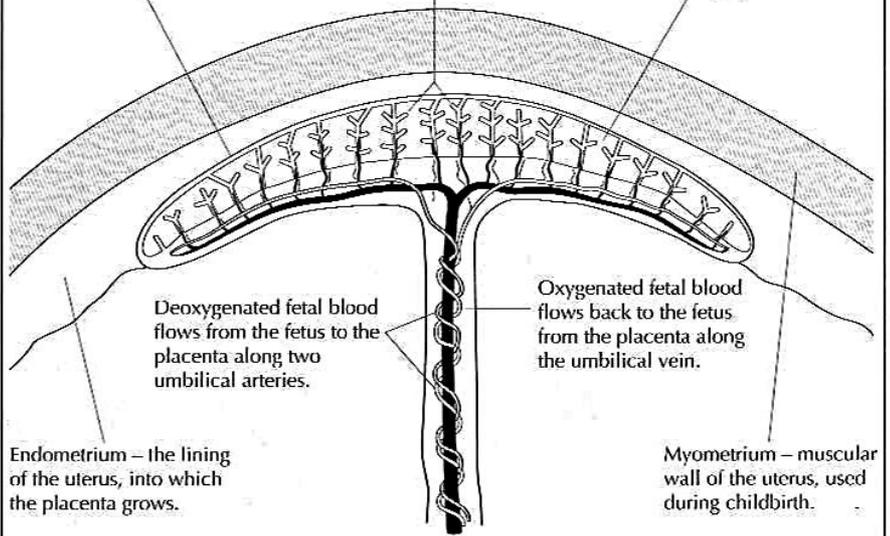
## EXCHANGE OF MATERIALS ACROSS THE PLACENTA



Maternal blood in the inter-villous space

Microvilli increase the surface area for the exchange

$O_2$, glucose, lipids, water, minerals, vitamins, antibodies, hormones

Chorion – forms the placental barrier, controlling what passes in each direction

Mitochondria provide ATP for active transport

Basement membrane (freely permeable)

Cytoplasm of chorion produces estrogen and progesterone and secretes them into the maternal blood

Capillary carrying fetal blood is close to the villus surface and has a very thin wall of single cells

small distance separating maternal and fetal blood

$CO_2$, urea, hormones, water

Connective tissue inside the villus

NB Maternal blood does not flow along the umbilical cord or through the fetus.

# EXAM QUESTIONS ON TOPIC 11

1  a)  Define *excretion*.                                                                    [2]

   b)  Compare the composition of blood plasma and urine, by giving two differences
       in the table below.                                                                    [2]

| Blood in the renal artery | Blood in the renal vein |
|---|---|
|  |  |
|  |  |

   c)  Explain briefly the function of the loop of Henle in the human kidney.                 [2]

   d)  Deduce which part of the kidney has been damaged if protein is found in the urine.     [1]

2  The electron micrograph below shows part of a myofibril, taken from a skeletal muscle. The parts marked
   M contain myosin filaments. Three other regions are labelled I, II and III.
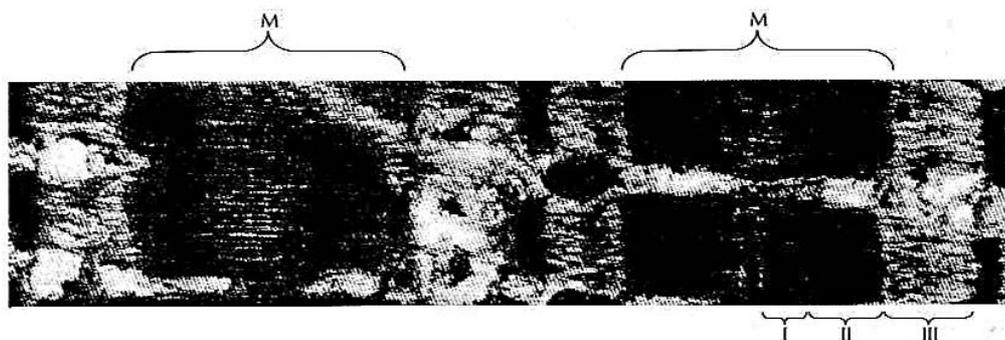


[Source: Dr G. Newman. EM Unit, University of Wales College of Medicine]

   a)  (i)   State one type of filament, apart from myosin, which is present in myofibrils.   [1]

       (ii)  Identify in which of the regions labelled I, II and III these other filaments can be found.  [1]

   b)  The myofibril is partly contracted. Deduce which of the regions would increase in length if

       (i)   the myofibril contracted more                                                    [1]

       (ii)  the myofibril relaxed                                                            [1]

3  a)  Compare the structure of human sperm and eggs.                                         [4]

   b)  Compare the role of FSH in men and women.                                              [3]

   c)  Compare the roles of LH and HCG in women.                                              [3]

# Distribution of plants and animals

## DISTRIBUTION OF PLANT SPECIES

The distribution of a species is the range of places that it inhabits. The distribution of plants is closely linked to the levels of abiotic factors in the environment. The main abiotic factors are **temperature, water, light, soil pH, salinity** and **mineral nutrients**. *Avicennia germinans*, for example, is a tree found in mangrove swamps on the coast of Mexico. It grows where the climate is hot and the soils are waterlogged and anaerobic, with high levels of salinity, a pH close to neutral and high levels of mineral nutrients. Few plants can grow in these conditions, but *Avicennia germinans* thrives.

Sometimes the distribution of a plant species shows what conditions a plant prefers. The figure shows the distribution of *Asperula cynanchica* in Britain and Ireland. It is found in areas with alkaline soils formed from chalk or limestone rock. It is absent from colder northern areas even where the soils are alkaline.

**Distribution of *Asperula cynanchica* (Squinancy Wort)**
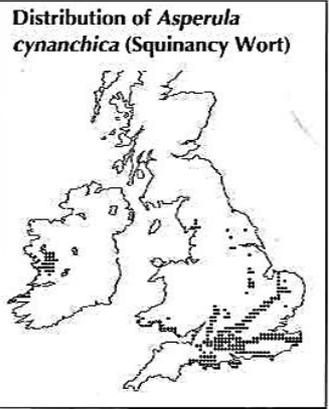


## DISTRIBUTION OF ANIMAL SPECIES

The distribution of animal species is affected by both abiotic and biotic factors.

- **Temperature** – external temperatures affect all animals, especially those that do not maintain constant internal body temperatures. Extremes of temperature require special adaptations, so only some species can survive them.
- **Water** – animals vary in the amount of water that they require. Some animals are aquatic and must have water to live in and at the other extreme some animals including desert rats are adapted to survive in arid areas where they are unlikely ever to drink water.
- **Breeding sites** – all species of animals breed at some stage in their life cycle. Many species need a special type of site and can only live in areas where these sites are available. For example, mosquitoes need stagnant water for egg laying.
- **Food supply** – many animal species are adapted to feed on specific foods and can only live in areas where these foods are obtainable. For example, blue whales feed mainly on krill and so congregate in areas of the ocean where krill is abundant.
- **Territory** – some species of animal establish and defend territories, either for feeding or breeding. This tends to give the species an even rather than a clumped distribution. Pairs of tawny owls defend a single territory throughout their adult lives.

## RANDOM SAMPLING USING QUADRATS

A sample is a part of a population, part of an area or some other whole thing, chosen to illustrate what the whole population, area or other thing is like. For example, a sample of a population is some individuals in the population but not all of them.

*In a random sample, every individual in a population has an equal chance of being selected.*

Random sampling of plant populations involves counting numbers in small, randomly located parts of the total area. The sample areas are usually square and are marked out using frames called **quadrats**.

A method for random sampling, using quadrats, is shown in the figure (right).

## TRANSECTS AND DISTRIBUTIONS

An alternative to random sampling is to investigate plant or animal distributions along a line marked out across a site. The line is called a **transect**.

Transects are particularly useful when there is a gradient in an abiotic variable. For example, if the soil in a valley is much wetter in the bottom of the valley than up the sides, a transect across the valley can be used to investigate this and the distributions of plant and animal species that are correlated with the variation in soil moisture content.

Transects can be used to investigate plant and animal distributions on seashores. The transect should be laid out at right angles to the high tide and low tide lines, so that it follows the gradient in time of inundation by sea water and time of exposure to air.

### Random sampling using quadrats

1. Mark out gridlines along two edges of the area.
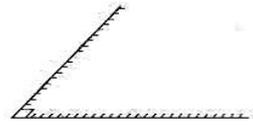


2. Use a calculator or tables to generate two random numbers, to use as co-ordinates and place a quadrat on the ground with its corner at these co-ordinates.

e.g. 14 and 7
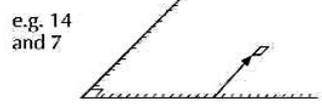


3. Count how many individuals there are inside the quadrat of the plant population being studied. Repeat stages 2 and 3 as many times as possible.



= 5 individuals
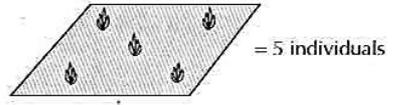
4. Measure the total size of the area occupied by the population, in square metres.
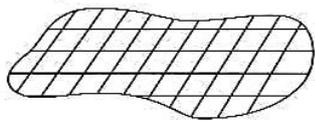


5. Calculate the mean number of plants per quadrat. Then calculate the estimated population size using this equation:

$$\text{population size} = \frac{\text{mean number per quadrat} \times \text{total area}}{\text{area of each quadrat}}$$

# Niches and interactions

## THE NICHE CONCEPT

Studies of the distributions of organisms and of interactions between organisms show that there are many different ways of existing in an ecosystem. The mode of existence of a species in an ecosystem is its ecological niche. The niche includes:

- **Habitat** – where the species lives in the ecosystem.
- **Nutrition** – how the species obtains its food.
- **Relationships** – the interactions with other species in the ecosystem.

If two species have a similar niche, they will compete in the overlapping parts of the niche, for example for breeding sites or for food. Because they do not compete in other ways, they will usually be able to coexist. However, if two species in an ecosystem have exactly the same niche they will compete in all aspects of their life and one of the two species will inevitably prove to be the superior competitor. This species will cause the disappearance of the other species from the ecosystem.

The principle that only one species can occupy a niche in an ecosystem is called the **competitive exclusion principle**.

## FUNDAMENTAL AND REALIZED NICHES

The niche that a species could occupy is often smaller than the niche that the species actually occupies. These potential and actual niches are called the **fundamental niche** and the **realized niche** of the species. Differences between the fundamental and realized niches are due to competition.

Other species prevent a species from occupying part of its fundamental niche by out-competing or by excluding it in some other way.

*The fundamental niche of a species is its potential mode of existence, given the adaptations of the species.*

*The realized niche of a species is its actual mode of existence, which results from its adaptations and competition from other species.*

Competitive exclusion happens when a species is unable to occupy any part of its fundamental niche in an area, so it has no realized niche in that area.

## INTERACTIONS BETWEEN SPECIES

All living organisms are affected by the activities of other living organisms. A situation in which two species affect each other is called an interaction. The table below shows a classification of interactions.

| Interaction | Terrestrial example | Marine example |
|---|---|---|
| **Herbivory** – a primary consumer feeding on a plant or other producer. The producer's growth affects food availability for the herbivore. | The beetle *Epitrix atropae* feeds only on leaves of *Atropa belladonna*, often causing severe damage to them. To most other organisms the leaves are highly toxic. | Algae growing on rocks in shallow seas are often heavily grazed. For example, a snail *Lacuna pallida* feeds on the brown seaweed *Fucus serratus* on rocky shores in Europe. |
| **Predation** – a consumer feeding on another consumer. The numbers and behaviour of the prey affect the predator. | The Canada lynx is a predator of the Arctic hare. Changes in the numbers of hares (up or down) are followed by similar changes in lynx numbers. | Bonitos feed on anchovetas in the Pacific Ocean west of Peru. When the anchoveta population crashed in the 1970s starving bonitos were found, with completely empty stomachs. |
| **Parasitism** – a parasite is an organism that lives on or in a host and obtains food from it. The host is always harmed by the parasite. | The tick *Ixodes scapularis* is a parasite of deer and of white-footed mice in northeast USA. The tick feeds by sucking blood from its hosts and therefore weakens them. | Organisms that cause infectious diseases are all parasites. For example, *Sphingomonas* bacteria cause a disease in elliptical star corals on the Florida reef. |
| **Competition** – two species using the same resource compete if the amount of the resource used by each species reduces the amount available to the other species. | Douglas Fir and Western Hemlock grow together in mixed forests in Oregon and other states in northwest USA, competing with each other for light, water and minerals. | Species of coral compete with each other on coral reefs. *Pocillopora damicornis* competes with many other corals, including *Pavona varians*, which benefit when predators feed on *Pocillopora damicornis*. |
| **Mutualism** – mutualists are members of different species that live together in a close relationship, from which both benefit. | *Usnea subfloridana* and other lichens consist of a fungus and an alga growing mutualistically. The alga supplies foods made by photosynthesis and the fungus absorbs mineral ions. | The cleaner wrasse is a small fish of warm tropical seas that cleans parasites from the gills and body of larger fish such as reticulate damsel fishes. The cleaner benefits because the parasites that it removes are its food. |

# Biomass and trophic levels

## MEASURING BIOMASS

Ecologists often use a measure called biomass.

*Biomass is the total dry mass of organic matter in organisms or ecosystems.*

For example, if an ecologist wanted to compare the amounts of organisms in each trophic level in an ecosystem, biomass might be used. Measuring biomass is a destructive technique, so the samples used are as small as possible.

### Method
1. Representative samples of all living organisms in the ecosystem are collected, for example from randomly positioned quadrats.
2. The organisms are sorted into trophic levels.
3. The organisms are dried, by being placed in an oven at 60–80°C.
4. The mass of organisms in each trophic level is measured using an electronic balance.
5. Drying and measuring the mass may be repeated to check that samples were completely dry.

## DIFFICULTIES WITH TROPHIC LEVELS

Sorting organisms into trophic levels can cause considerable difficulties. This is because many species exist partly in one trophic level and partly in another. The following examples illustrate this.

- Euglena, a unicellular organism found in ponds, has chloroplasts and photosynthesizes, but it also feeds heterorophically by endocytosis.
- Chimpanzees mainly feed on fruit and other plant matter, but they also sometimes eat termites and even larger animals such as monkeys, so they are both first and second consumers.
- Herring are second consumers when they feed on *Calanus* (a copepod) and other first consumers but they are third consumers when they feed on sand eels and other second consumers.
- Oysters (*Ostrea* species) and many other filter feeders consume both ultraplanktonic producers and microplanktonic consumers, so they are first and second consumers. They also consume dead organic matter, so they are also detritivores.

It is difficult to decide into which trophic level these types of organism should be classified. One practical solution is to classify each species according to its main food source.

## CONSTRUCTING PYRAMIDS OF ENERGY

Pyramids show the energy flow through each trophic level in an ecosystem. To construct a pyramid of energy, energy flow through each species in the ecosystem must be measured. In each trophic level the energy flow through all species is added up.

The lowest bar of a pyramid of energy is the total amount of energy that flows through the producers in the ecosystem. This is also called gross production.

*Gross production is the total amount of organic matter produced by plants in an ecosystem.*

Gross production and all the other energy flows in a pyramid are measured in kilojoules of energy per square metre per year ($kJ\ m^{-2}\ year^{-1}$).

Gross production does not have to be measured directly, as it can be calculated from net production and plant respiration.

*Net production is the amount of gross production in an ecosystem remaining after subtracting the amount used by plants in respiration.*

gross production = plant respiration + net production

*Example – an old field community in Michigan, USA.*
net production = $20.79 \times 10^3\ kJ\ m^{-2}\ year^{-1}$
plant respiration = $3.68 \times 10^3\ kJ\ m^{-2}\ year^{-1}$
gross production = $(20.79 + 3.68) \times 10^3\ kJ\ m^{-2}\ year^{-1}$
= $24.47 \times 10^3\ kJ\ m^{-2}\ year^{-1}$

The upper bars of a pyramid of energy are the total amounts of energy that flow through the various groups of consumers. This is the amount of energy in the food that the consumers ingest.

The data below was obtained from an Arctic tundra ecosystem on Devon Island in northern Canada.

| Trophic level | Energy flow ($kJ\ m^{-2}\ year^{-1}$) |
| --- | --- |
| Producers | 4925 |
| Primary consumers | 24 |
| Secondary consumers | 4 |

This data can be used to construct a pyramid of energy. Each bar of the pyramid should be drawn to the same scale and labelled with the trophic level.

## NUMBERS AND BIOMASS OF ORGANISMS IN HIGHER TROPHIC LEVELS

Pyramids of energy show that there are large losses of energy at each trophic level. Reasons for losses of energy are explained on page 41. Losses of energy in ecosystems are accompanied by losses of biomass.

Respiration is an example of a process in which both energy and biomass are lost. When glucose or another respiratory substrate is oxidized in respiration, energy from the glucose is released for use in the cell and is then lost as heat. The mass of the glucose does not disappear – it passes into the carbon dioxide and water that are produced in respiration. When

these waste products are excreted, biomass is lost. As a result of respiration and other processes, both energy and biomass are lost at each stage in a food chain.

The energy content per gram of food does not decrease along a food chain. If anything, the food eaten by the higher trophic levels is richer in energy per gram than that eaten by lower trophic levels. However, the total biomass of food available to higher trophic levels is very small. It cannot support large numbers of organisms, especially if these organisms need to be large to overpower their prey. Higher trophic levels therefore usually contain very small numbers of large organisms, with a low total biomass per unit area.

# Succession and biomes

## ECOLOGICAL SUCCESSION

An ecological succession is a series of changes to an ecosystem, caused by complex interactions between the community of living organisms and the abiotic environment. Two types of succession are recognized:

**Primary succession** starts in an environment where living organisms have not previously existed, for example a new island, created by volcanic activity.

**Secondary succession** occurs in areas where an ecosystem is present, but is replaced by other ecosystems, because of a change in conditions. For example, abandoned farmland developing into forest.

During an ecological succession, the community causes the abiotic environment to change. As a result, some species die out and others join the community. Although the community may continue to change in this way for hundreds of years, eventually a stable community develops, called the climax community.

The changes to the abiotic environment during ecological successions vary, but some often occur.

- The amount of organic matter in the soil increases as organic matter released by plants and other organisms accumulates.
- The soil becomes deeper as organic matter helps to bind mineral matter together.
- The soil structure improves as the organic matter content rises, increasing the amount of water that can be retained and the rate at which excess water drains through.
- Soil erosion is reduced by the binding action of the roots of larger plants.
- The amounts of mineral recycling increases, as the soil can hold larger amounts and more minerals are held in the increasing biomass of the community.

## BIOMES AND BIOSPHERE

Ecological succession usually stops when a stable ecosystem develops that contains a group of organisms called the climax community. Different types of ecosystem develop in different parts of the world. A type of ecosystem is called a **biome**.

**Rainfall** and **temperature** are the two main factors that determine what type of ecosystem develops in an area, and therefore what the distribution of biomes around the world is. The climograph below shows the relationship between the levels of these two factors and the types of biome. The characteristics of six major biomes are described below.

The biomes of the world together make up the **biosphere**. It is now well known that the ecosystems and biomes of the world function as one overall ecological system, so the biosphere is the thin layer of interdependent and interrelated ecosystems and biomes that cover the Earth.



NB. This climograph shows probable biomes at particular levels of rainfall and temperature, but other factors, including fire, affect distribution of biomes.

## AN EXAMPLE OF PRIMARY SUCCESSION

On the slopes of Volcan Osorno, in southern Chile, there are large areas of bare volcanic ash, released during recent eruptions of the volcano. Adjacent areas show the stages in an ecological succession.

- Mosses spread over the ash, eventually forming a complete cover.
- Small herbs join the mosses.
- Shrubs, including *Pernettya*, *Eucryphia* and *Embothrium*, enter the community and gradually replace the herbs and mosses.
- Trees, including *Nothofagus*, gradually spread to replace the shrubs with dense forest.

**A stage in succession to forest on Volcan Osorno**



## MAJOR BIOMES OF THE WORLD

| Desert | Rainfall very low; warm to very hot days and cold nights. | Very few plants, some storing water and some growing quickly after rain. |
|---|---|---|
| Grassland | Rainfall low; warm or hot summers and cold winters. | Dominated by grasses and other herbs that can withstand grazing. |
| Shrubland | Cool wet winters and hot dry summers, often with fires. | Drought-resistant shrubs dominate, often with evergreen foliage. |
| Temperate deciduous forest | Moderate rainfall with warm summers and cool winters. | Trees that shed their leaves in the winter dominate with shrubs and herbs beneath. |
| Tropical rainforest | Rainfall high to very high and hot or very hot in all seasons. | A huge diversity of plants: tall evergreen trees, smaller trees, shrubs and herbs. |
| Tundra | Very low temperatures; little precipitation mostly as snow. | Very small trees, a few herbs, mosses and lichens are present. |

# Biodiversity and rainforests

## BIODIVERSITY
The word biodiversity was only invented in 1986. It is an abbreviation of 'biological diversity' and encompasses the diversity of ecosystems on Earth, the diversity of species within them, and the genetic diversity of each species. One of the main tasks of ecologists is conservation of the world's biodiversity.

## THE SIMPSON DIVERSITY INDEX
It is sometimes useful to have an overall measure of species richness in an ecosystem. The Simpson index is one of the most commonly used.
*Method*
1. Use a random sampling technique to search for organisms in the ecosystem.
2. Identify each of the organisms found.
3. Count the total number of individuals of each species.
4. Calculate the index (D).

$$D = \frac{N(N-1)}{\Sigma\, n(n-1)}$$

$N$ = total number of organisms
$n$ = number of individuals per species

*Example*
Organisms were found and identified in the River Enningdalselva in a part of Sweden where some lakes and rivers have been affected by acid rain. Six sites in the river were chosen randomly and kick sampling was used at each site along a 10 m transect. Nets with a 25 cm × 25 cm opening and 0.5 mm mesh were used. The results are shown in the table below.

| Group | Species | Name | |
|---|---|---|---|
| Ephemerida | *Dixa* species | Mayfly larva | 8 |
| Odonata | *Tipula* species | Dragonfly larva | 5 |
| Trichoptera | Species unidentified | Caddisfly larva | 4 |
| Plecoptera | *Nemoura variegata* | Stonefly larva | 4 |
| Hemiptera | *Gerris* species | Pond skater | 3 |
| Isopoda | *Asellus aquaticus* | Water louse | 2 |
| Acari | *Arrhenurus* species | Water mite | 1 |
| Platyhelminth | *Dendocoelum lact.* | Flatworm | 4 |
| Platyhelminth | *Dugesia* species | Flatworm | 3 |
| Hirundinea | Species unidentified | Leach | 1 |
| Oligochaeta | *Lumbriculides* | Annelid worm | 2 |
| Gastropoda | *Lymnaea* species | Snail | 4 |
| Bivalvia | *Margaritifer* | Pearl mussel | 1 |

$$D = \frac{42\,(42-1)}{140} = 12.3$$

The high diversity index suggests that the river has not been damaged by acid rain, or any other disturbance. This fits in with observations of a thriving salmon population in the river. If the Simpson diversity index was calculated for another river in the same area, or a river in the same biome elsewhere in the world, the ecological health of these rivers could be compared with River Enningdalselva. This would help to assess whether conservation measures were needed in any of the rivers. It would also allow rivers with high biodiversity to be identified and given appropriate conservation status, for example as nature reserves.

## RAINFOREST CONSERVATION
All of the world's biomes must be conserved, but tropical rainforests have been particularly threatened recently and there are many reasons for strenuous efforts to conserve them.

**Economic reasons**
- New commodities, for example medicines or materials, may be found in rainforest species.
- New crop plants or farm animals could be developed from rainforest species or existing varieties could be improved using their genes.
- Ecotourism could provide considerable income.

**Ecological reasons**
- Rainforests fix large amounts of carbon dioxide and, without them, the greenhouse effect and global warming would probably be more severe.
- Damage to rainforests can have widespread effects including soil erosion, silting up of rivers, flooding and even changes to weather patterns.

**Ethical reasons**
- Every species has a right to life, regardless of whether it is useful to humans or not.
- The wildlife of rainforests has cultural importance to the indigenous human populations and it is therefore wrong to destroy it.
- It would be wrong to deprive humans of the future the rich experiences that the Earth's biodiversity provide to us.

**Aesthetic reasons**
- Rainforests have species in them that are beautiful and give us great enjoyment.
- Painters, writers and composers have been and continue to be inspired by rainforests.

## BIOMAGNIFICATION
Some pollutants are absorbed into living organisms and accumulate because they are not efficiently excreted. When a predator consumes prey containing the pollutant and absorbs it, the level in the body of the predator rises and can reach levels much higher than those in the bodies of its prey. This increase is called biomagnification and it can happen at each stage in the food chain.

*Biomagnification is the process by which chemical substances become more concentrated at each trophic level.*

Polychlorinated biphenyls (PCBs) are chemicals that were used as insulators in electrical devices and as flame-retardants. It was shown as long ago as 1953 that moderate doses killed experimental rats, but manufacture continued until the 1970s.

PCBs have escaped into the environment and are now detectable throughout the world. They are both persistent and highly toxic. Bioaccumulation factors (BAF) for PCBs vary considerably. Examples are given below.

| Pathway | BAF |
|---|---|
| Soil to earthworm | 10 |
| Fish to bird or mammal | 90 |
| Water to fish | 50 000 |
| Water to shellfish | 10 000 000 |

# Impacts of humans on ecosystems

## IMPACTS OF ALIEN SPECIES

An alien species is a type of organism that humans have introduced to an area where it does not naturally occur. Alien species are sometimes very invasive and cause considerable ecological damage. For example, the floating fern, *Salvinia molesta*, has damaged many lakes in the tropics and sub-tropics. It grows rapidly, doubling the number of leaves in about two weeks, spreading over the water surface and eliminating native plant species by **interspecific competition**. It has been controlled by introducing another alien species – salvinia weevil (*Cyrtobagus salviniae*), which feeds on the floating fern. This is an example of **biological control**.

*Salvinia molesta* was deliberately transported around the world as an aquarium or pond plant. Alien species have also been introduced accidentally. For example, three species of rat were introduced to the mainland of New Zealand during the 19th century. They caused many species of bird to disappear from the mainland. This is called **species extinction**. Some of these birds were able to survive on islands that remained free of rats. Until the 1950s, Big South Cape Island in the far south of New Zealand remained rat-free and was a haven for many rare birds. Three types were, by then, found nowhere else: South Island saddleback, Stewart Island snipe and Stead's bush wren.

In the mid-1950s black rats (*Rattus rattus*) reached Big South Cape Island. Their numbers rose exponentially and by 1964 there were huge numbers on the island. They attacked eggs, young birds in nests and even adult birds, which were not behaviourally adapted to resist them. This is an example of alien species causing damage by **predation**.

It became obvious that human intervention was needed to save the three rarest species of bird. Ecologists from the New Zealand Wildlife Service trapped as many of the remaining individuals as they could. Only two Stewart Island snipe were trapped and they died soon after, so this species became extinct. Nine Stead's bush wrens were trapped and transferred to another island that was still rat-free. Unfortunately they failed to breed and gradually died out, so this species also became extinct. Forty-one South Island saddlebacks were caught and transferred to two other rat-free islands. They survived and bred and were eventually distributed to other islands. In the 1980s they were re-introduced to Little Barrier Island after another alien species had been eliminated – wild cats.

The South Island saddleback was the first species of bird to be saved from extinction by human intervention. Its future for the moment seems relatively secure.



South Island Saddleback
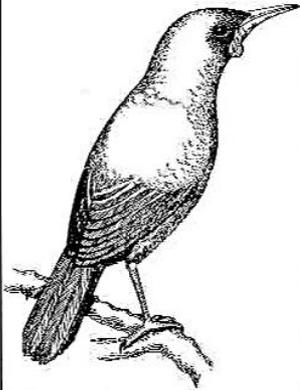


Islands in the far south of New Zealand

South Island of New Zealand is 20km to the north

Stewart Island

Big South Cape Island
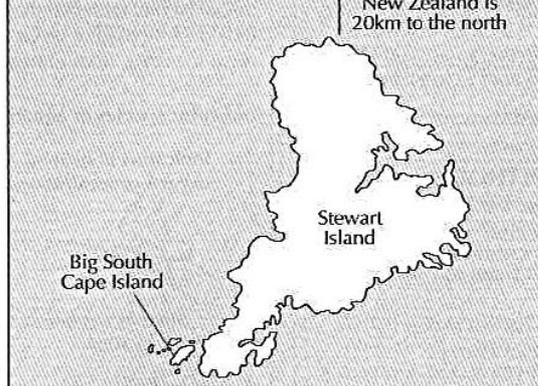


Stead's bush wren
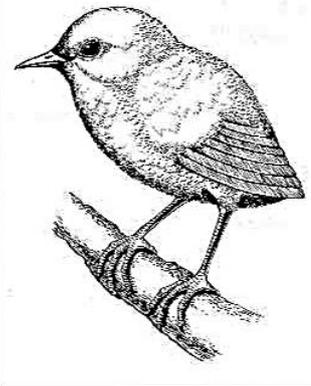
## OZONE AND ULTRA-VIOLET RADIATION

Ultra-violet radiation has very damaging effects on living organisms and biological productivity.

- It increases mutation rates, by causing damage to DNA.
- It can cause cancers, especially of the skin.
- It causes severe sunburn and cataracts of the eye.
- It reduces photosynthesis rates in plants and algae and so affects food chains.

The amount of damaging ultra-violet radiation reaching the Earth's surface would be much greater without the ozone layer in the atmosphere. Ozone absorbs shortwave radiation, especially ultra-violet. At low altitudes in the atmosphere, the concentration of ozone is usually about 0.01 ppm, but at 20–50 km above the Earth's surface, in the stratosphere, ozone is much more concentrated – about 1–10ppm. This is the ozone layer.

Measurements of ozone concentrations in the stratosphere have shown that there has been depletion throughout the world. Since the 1980s an ozone 'hole' has appeared over the Antarctic every year between September and October, which persists for several months.

CFCs are the main cause of ozone depletion. They are chemical compounds manufactured by humans and released into the atmosphere. Ultra-violet light causes CFCs to dissociate and release atoms of chlorine. These chlorine atoms are highly reactive and cause complex reactions in which ozone is converted to oxygen. The reactions form a cycle, with the chlorine atoms being released again, so that they can go on to cause the destruction of more ozone. One chlorine atom can potentially cause the destruction of hundreds of thousands of ozone molecules.

## IN-SITU CONSERVATION METHODS

The best place to conserve a species is in its own habitat. This is called *in situ* conservation. Many terrestrial and marine nature reserves have been established for this purpose, but other areas can also be important, including farmland and gardens.

*In situ* conservation has several advantages.
• Species remain adapted to their habitats.
• Greater genetic diversity can be conserved.
• Animals maintain natural behaviour patterns.
• Species interact with each other, helping to conserve the whole ecosystem.

The size and shape of nature reserves affects their conservation value. The distribution of ecosystems within a nature reserve is also important. These are the **biogeographical features** of a nature reserve. Large nature reserves usually promote conservation of biodiversity more effectively than small ones. The ecology of the edges of ecosystems is different from the central areas, due to edge effects. An example of an edge effect is the egg-laying habits of the cowbird of the western United States. It feeds in open areas on insects disturbed by large grazing mammals, but it lays its eggs in the nests of songbirds, near the edges of forests. Fragmentation of forests has led to a considerable increase in cowbird populations and the nest parasitism due to them, because of the increase in forest edge.

Where a habitat is fragmented, wildlife corridors can be very valuable in allowing organisms to move between different areas, for example tunnels under busy roads.

## EX-SITU CONSERVATION METHODS

Despite the advantages of *in situ* conservation, it is not always enough to ensure the survival of a species.

• Some species become so rare that it is not safe to leave them unprotected in the wild.
• Sometimes destruction of a natural habitat makes it essential to remove threatened species from it.

In these situations ex *situ* measures are needed.

1. **Captive breeding** – some or all members of a species are caught and moved to a zoo, where they are encouraged to breed. When numbers are high enough, some are returned to the wild to re-establish a natural population. An example of a species helped by captive breeding is the Hawaiian kestrel.
2. **Botanic gardens** – sites where many different species of plants are cultivated, either in greenhouses or in the open. One of the largest, the Royal Botanic Gardens of Kew, has more than 50000 of the world's 250000 known species in its collection.
3. **Seed banks** – seeds are kept in cold storage at –10°C to –20°C. Seeds of most species remain viable for more than a hundred years in these conditions. Other species that are not as long lasting can be germinated and grown to produce replacement seed before viability is lost. The Kew Millennium Seed Bank will eventually hold seed of 25000 endangered species.

## ACTIVE MANAGEMENT TECHNIQUES

Some pristine nature reserves can be left in their natural state, but often humans have caused changes and active management is therefore needed to ensure the survival of rare or endangered species. The Hinewai Reserve in the South Island of New Zealand is a good example of limited, but effective, management. Valleys that had been cleared of native forest to become farmland have been allowed to revert to native forest, by secondary succession. Active conservation measures have included the culling of goats. They are an alien species and damage native plants by grazing. Native plants are now re-establishing at Hinewai at an amazing rate.

## MONITORING ENVIRONMENTAL CHANGE

Problems in natural ecosystems are detected quickly if there is frequent environmental monitoring. Abiotic factors can be measured directly, but another useful technique is the use of living organisms to detect changes. Indicator species are very useful, as they need particular environmental conditions and therefore show what the conditions in an ecosystem are. Lichens are valuable indicator species because their tolerance of sulphur dioxide varies considerably from the most tolerant to the least tolerant species. Indicator species are also often used to assess pollution levels in aquatic ecosystems. Stonefly, mayfly and caddisfly larvae (below) require unpolluted, well-oxygenated water. Other aquatic species, including chironomid midge larvae, rat-tailed maggot larvae and tubifex worms, indicate low oxygen levels and excessive levels of suspended organic matter, from untreated sewage for example.

**Indicator species in aquatic ecosystems**

Indicators of high oxygen concentrations

Indicators of low oxygen concentrations
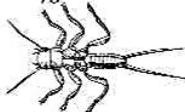
**Stonefly nymph** (up to 30mm)

**Chironomid** (bloodworm: a midge larva) (up to 20mm)

**Mayfly larva** (up to 15mm)
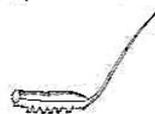
**Rat-tailed maggot larva** (up to 55mm including tube)

**Caddisfly larva** (up to 30mm)

**Tubifex** (sludge worm) (up to 40mm)

To obtain an overall environmental assessment of a river or other ecosystems, a biotic index can be calculated. There are various methods, which usually involve multiplying the number of individuals of each indicator species by its pollution tolerance rating. An abundance of tolerant species gives a low overall score and an abundance of intolerant species gives a high score.

# 🅗🅛 Population ecology

## ESTIMATING ANIMAL POPULATION SIZES

It is usually impossible to count every individual in a population. Instead an accurate estimate is made. Ecologists often need to measure the size of a population. There are many methods for making estimates of population size. The **capture–mark–release–recapture method** is suitable for animals that move around and are difficult to find.

## CAPTURE–MARK–RELEASE–RECAPTURE METHOD

1. Capture as many individuals as possible in the area occupied by the animal population, using netting, trapping or careful searching

e.g. careful searching for banded snails (*Cepaea nemoralis*)
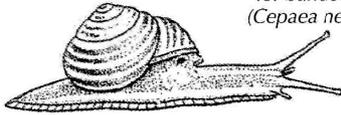
2. Mark each individual, without making them more visible to predators.
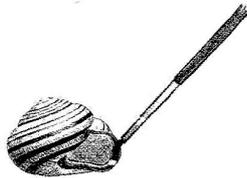
e.g. marking the inside of the snail shell with a dot of non-toxic paint.

3. Release all the marked individuals and allow them to settle back into their habitat.
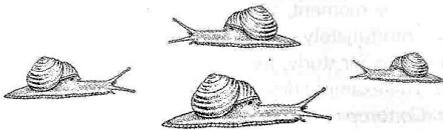
4. Recapture as many individuals as possible and count how many are marked and how many unmarked.

24 marked

16 unmarked

5. Calculate the estimated population size by using the Lincoln index:

$$\text{population size} = \frac{n_1 \times n_2}{n_3}$$

$n_1$ = number caught and marked initially
$n_2$ = total number caught on the second occasion
$n_3$ = number of marked individuals recaptured

## *r*-STRATEGIES AND *K*-STRATEGIES

Living organisms differ greatly in their life cycles and their patterns of reproduction. As a result, there are different patterns of population growth. Natural selection can cause these characteristics to change, so that they are adapted to the niche of a species. Two extreme patterns of population growth have been defined.

### Strategies for an unstable environment

In an unstable environment, life expectancy is very short and few individuals survive long enough to reproduce even once. The population of a species in these environmental conditions is unlikely ever to become large enough for density-dependent factors such as competition to become important. The most successful species use *r*-strategies:

- only growing to a small body size, which can be quickly reached
- maturing early, so reproduction happens while still young
- reproducing once only, with all available energy and resources devoted to it
- producing many offspring, with a relatively small body size
- giving offspring little or no parental care.

If all or most offspring survived and reached reproductive maturity, there would be exponential population growth and probably over-population. With *r*-strategists this is very unlikely because the chance of survival of their offspring is so small.

### Examples of *r*-strategists
*Eschscholtzia californica* (Californian poppy)
*Lemmus lemmus* (lemming)
*Clupea harengus* (herring)

### Strategies for a stable environment

In a stable environment, life expectancy is much longer and many individuals will survive long enough to reproduce repeatedly. The population of a species in these environmental conditions is likely to become large enough for density-dependent factors such as competition to become important. The most successful species use *K*-strategies:

- growing to a large body size, which is an advantage in intra-specific competition
- maturing late, with reproduction not beginning until an individual is relatively old
- reproducing more than once and sometimes many times during the extended life-span
- producing few offspring, with a relatively large body size
- giving much parental care to offspring.

Larger numbers of small offspring would make a higher rate of population growth possible. With *K*-strategists, rapid population growth is unlikely ever to continue for long, because it will lead to intense competition. Small offspring, or offspring that are not nurtured by their parents, are unlikely to compete effectively enough to reach adulthood.

### Examples of *K*-strategists
*Quercus petraea* (sessile oak tree)
*Loxodonta africana* (African elephant)
*Dermochelys coriacea* (leatherback turtle)

## SUSTAINABLE YIELDS OF FISH

Wild populations of fish are an important food source for many human populations. They are a renewable resource – a resource that need never run out, if it is used in a sustainable way. A renewable resource is constantly replaced or replenished, in the case of fish by them reproducing and growing.

Sustainable use of renewable resource means harvesting at a rate that avoids a decline in the resource. This is particularly important with fish populations. If they are over-exploited and the numbers of adult fish fall below a critical level, spawning fails. The disastrous collapse in the Peruvian anchoveta fishery is an example of this. Industrial scale exploitation of the anchoveta began in 1940 and grew at a rapid rate until 1973, when the annual catch dropped from 12 million tonnes to zero. The fall in anchoveta egg production in the years preceding the population crash is shown in the graph below. An El Nino event was partly responsible, but over-fishing was also a major factor.

**Graph showing a collapse in anchoveta egg production**
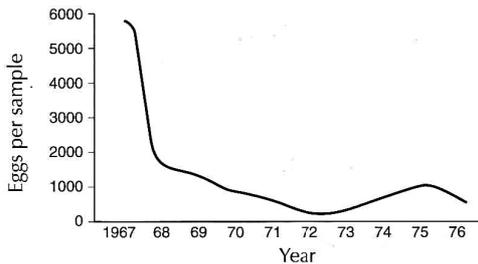


With fisheries, sustainable use means not catching fish faster than the stocks can replenish themselves. The **maximum sustainable yield** is the largest amount that can be harvested without a decline in stocks. One of the aims of research into fisheries is to determine what the maximum sustainable yield of particular fisheries is. International co-operation is then usually needed to ensure that this yield is not exceeded.

## INTERNATIONAL CONSERVATION OF FISH

International measures are needed to promote fish conservation because most fish live in international waters, where ships from any country can catch fish. Various measures would help.

- Monitoring of stocks and of reproduction rates.
- Quotas for catches of species with low stocks.
- Closed seasons in which fishing is not allowed, especially during the breeding season.
- Exclusion zones in which fishing is banned.
- Moratoria on catching endangered species.
- Minimum net sizes, so that immature fish are not caught.
- Banning of drift nets, which catch many different species of fish indiscriminately.

Some of these measures have been used already in parts of the world, with limited success. Enforcement is very difficult and relies on a level of international trust and co-operation that is not always seen.

## ESTIMATING SIZES OF FISH STOCKS

It is very difficult to estimate the size of commercial fish stocks accurately. This is because fish cannot be seen from above the water surface and many species move around rapidly or are not distributed evenly, so random sampling methods are ineffective.

The usual method of estimating stocks involves collecting data on fish catches. The numbers of fish of each age are counted and an age distribution for the population is obtained. Survivorship curves and spawning rates can then be deduced, from which estimates of the total stock can be made. However there are great uncertainties, for example what proportion of the total population has been caught. Capture–mark–release–recapture methods have been used, with fish marked using internal or external tagging. This method can work well in lakes, but it is less successful in the open sea. By the time the marked fish have mixed back into the overall population by migration, the proportion of marked fish that can ever be recaptured is too small for accurate estimates of the size of the stock.

Other methods of estimation of fish stocks have been used in specific situations. Echo sounders can be used to measure the size of shoals of fish, or even single fish in some cases. The fish must not be swimming too deeply and trawls must also be used for calibration and to check which species of fish has been detected by the echolocation.

None of these methods can estimate stocks with anything approaching certainty and, as a result, disputes between the fishing industry and conservation agencies about stocks are very common.

## EXTINCTION OF SPECIES

When the last members of a species die, the species becomes extinct. The rate of species extinctions is probably at an all-time high at the moment, as a result of human activities. There are unfortunately many extinct species from which to select examples for study, including the passenger pigeon and the dodo. The example described here is the Carolina parakeet, *Conuropsis carolinensis*.

These brightly coloured parrots (right) were once common in forests to the east of the Mississippi, from New York to Florida, feeding on seeds of trees and herbs. Clearance of forests reduced their habitat and they started to feed on crops. Farmers killed many of them. Others were caught to obtain feathers, which were used to make fashionable women's clothing. They were also trapped and kept as pets. By 1900 there were no Carolina parakeets in the wild and the last specimen died in Cincinnati Zoo in 1918.
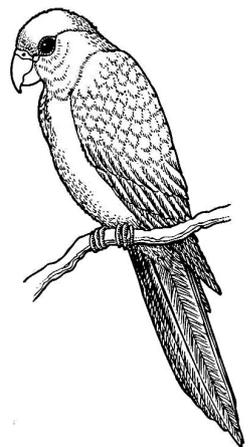
# EXAM QUESTIONS ON OPTION G – ECOLOGY AND CONSERVATION

G1 Food chains are difficult to study in natural ecosystems, so a group of ecologists set up communities in culture vessels. They used them to investigate the effects of varying nutrient concentrations. In all of the vessels an aquatic bacterium, *Serratia marcescens,* was present. Three concentrations of the nutrients on which *S. marcescens* feeds were used. In some of the cultures *Colpidium striatum,* a predator of *S. marcescens,* was added. In some of these cultures *Didinium nasutum,* a predator of *C. striatum,* was added. The cultures therefore each had one, two or three trophic levels. The population density of *S. marcescens* at the end of the experiment is shown in the bar chart below.
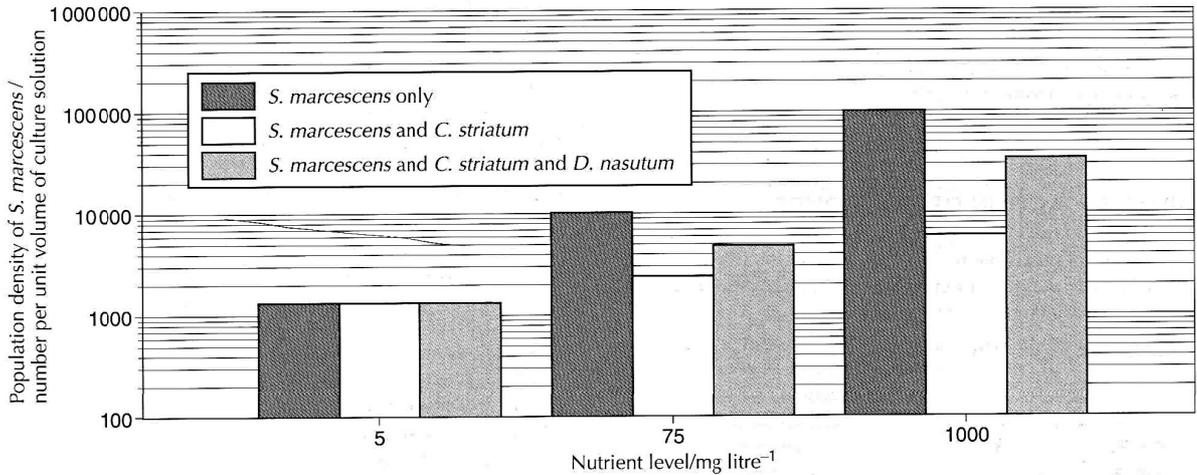


[Source: Kaunzinger, *Nature* (1998), 395, pages 495–496]

a) (i) Explain the effect of the nutrient concentration on the population density of *S. marcescens.*  [1]

   (ii) Explain the effect of the presence of *C. striatum* on the population density of *S. marcescens.*  [1]

   (iii) Explain the effect of the presence of *D. nasutum* on the population density of *S. marcescens.*  [2]

b) In the culture with the lowest nutrient level *D. nasutum* eventually died out but *C. striatum* survived. Explain the reasons for *D. nasutum* dying out.  [2]

c) Using the results of this investigation, predict a relationship between nutrient levels and length of food chain in natural ecosystems.  [1]

G2 a) Explain how indicator species may be used.  [2]

   b) Outline two *ex situ* methods of conservation of endangered species.  [2]

G3 The graph below shows inputs of mercury from the UK to marine waters and flow rates of rivers, between 1990 and 2004, as a percentage of levels in 1990.
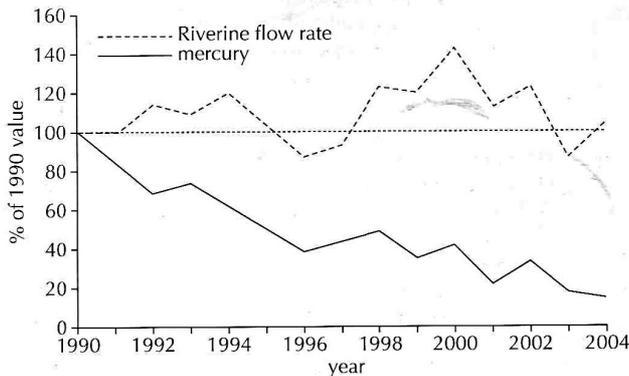


a) State the trend in mercury inputs from the UK to marine waters.  [1]

b) Using the data in the graph, deduce the reasons for fluctuations, from year to year, in mercury inputs.  [2]

c) Biomagnification of mercury can occur in marine ecosystems. Suggest two consequences of biomagnification of mercury in ecosystems.  [2]

## ⓗ Hormonal control

### HORMONES

Hormones are chemical messengers, secreted by endocrine glands directly into the blood. The blood carries them to target cells. where they elicit a response. A wide range of chemical substances is used as hormones in humans:

**Steroids**
e.g. estrogen, progesterone, testosterone
**Peptides**
e.g. insulin, ADH, FSH, LH
**Tyrosine derivatives**
e.g. thyroxin

### MODE OF ACTION OF HORMONES

Hormones do not all work in the same way. There are two main types of mechanism.

1. Steroid hormones enter target cells by passing through the plasma membrane. They bind to receptor proteins in the cytoplasm of target cells, to form a hormone–receptor complex. This complex acts as a regulator of gene transcription, by binding to specific genes. Transcription of some genes is promoted; other genes are inhibited. In this way steroid hormones control whether or not particular enzymes or other proteins are synthesized. They therefore can help to control the activity and development of target cells.
2. Peptide hormones do not enter cells. Instead they bind to receptors in the plasma membrane of target cells. The binding of the hormone causes the release of a secondary messenger inside the cell. The secondary messenger causes a change to the activities of the cell, usually by activating or inhibiting an enzyme.

### HYPOTHALAMUS AND PITUITARY GLAND

The hypothalamus is a small part of the brain that links the nervous and endocrine systems. It controls hormone secretion by the pituitary gland located below it (shown in the figure, above right). The anterior and posterior lobes of the pituitary gland are controlled in a different way by the hypothalamus:

**Anterior pituitary** – neurosecretory cells in the hypothalamus secrete hormones, called releasing hormones, into capillaries in the hypothalamus. These capillaries join to form a blood vessel that lead to the capillaries in the anterior pituitary. This vessel is a portal vein – an unusual type of blood vessel that carries blood directly from one capillary network to another. The releasing hormones stimulate the anterior pituitary to secrete hormones. For example, GnRH stimulates the release of FSH and LH.

**Posterior pituitary** – neurosecretory cells in the hypothalamus synthesize hormones, pass them via axons to nerve endings in the posterior pituitary and control their secretion. The secretion of ADH is controlled in this way (see right).

### Structures of the hypothalamus and pituitary gland



Cell bodies of neurosecretory cells in two hypothalamic nuclei (other nuclei indicated by dotted lines)

Neurosecretory cells with nerve endings on the surface of blood capillaries

HYPOTHALAMUS (area inside dashes)

Portal vessel, linking two capillary networks

Network of capillaries receiving hormones from neurosecretory cells

Nerve tracts containing axons of neurosecretory cells

Network of capillaries that release hypothalamic hormones and absorb anterior pituitary hormones

Nerve endings of neurosecretory cells secreting hormones into capillaries (not shown)

POSTERIOR LOBE OF PITUITARY GLAND    ANTERIOR LOBE OF PITUITARY GLAND

### CONTROL OF ADH SECRETION

Neurosecretory cells in the supra-optic nucleus of the hypothalamus synthesize ADH, transport it down their axons and store it in nerve endings in the posterior pituitary gland. Osmoreceptor cells in the hypothalamus monitor the concentration of the blood plasma. If the plasma becomes too concentrated, impulses are passed to the ADH-secreting neurosecretory cells, which convey the impulses to their nerve endings in the posterior pituitary. The impulses stimulate release of ADH into the blood from the stores in the nerve endings. ADH causes a reduction in the concentration of the blood plasma, by stimulating the kidney to produce hypertonic urine (see page 102).

If the osmoreceptor cells detect that the concentration of blood plasma is too low, the neurosecretory cells are not stimulated to release ADH and the blood ADH level rapidly drops, allowing larger volumes of dilute hypotonic urine to be excreted.

## SUMMARY OF DIGESTION

Food is digested as it passes along the alimentary canal, from the mouth to the anus. Longitudinal and circular muscle fibres in the wall of the alimentary canal contract and relax, squeezing the food and breaking up large solid lumps. Digestive juices, containing enzymes, are mixed with the food. The enzymes digest proteins, nucleic acids, starch and other macromolecules. Digestive juices are secreted by the salivary glands, by glands in the wall of the stomach and by the pancreas. These are all examples of exocrine glands.

Some macromolecules cannot be digested by humans, for example cellulose. The enzyme cellulase digests cellulose, but humans lack the gene that codes for this enzyme, and so cannot make it.

Undigested cellulose is an important part of dietary fibre, which has beneficial effects on the digestive system.

## EXOCRINE GLANDS

The secretory cells in an exocrine gland are in a layer that is only one cell thick. The total area of the layer of secretory cells can be very large because of invagination and branching. The digestive juice is released from the cells by exocytosis. It is then discharged from the gland by travelling along ducts. One group of secretory cells, clustered around the end of a duct, is called an **acinus**.
The ducts and acini in part of the pancreas that secretes pancreatic juice are shown below.

**Structure of exocrine gland tissue in the pancreas**



*labels: secretory vesicles · one acinus · secretory cells · basement membrane · wall of duct · lumen of duct*
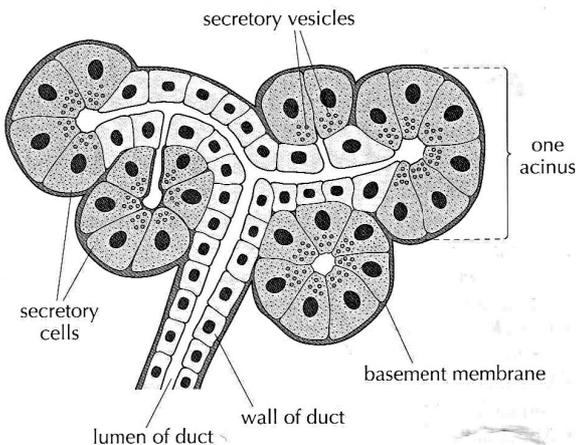
## EXOCRINE GLAND CELLS

Exocrine gland cells have distinctive features.
- One or two prominent nucleoli inside the nucleus, for production of ribosome subunits.
- An extensive area of rough endoplasmic reticulum, for protein synthesis.
- Golgi apparatuses for processing proteins.
- Many large vesicles, sometimes called secretory granules, for storage of the substances being secreted and transport of them to the plasma membrane. The vesicles are usually densely stained because of the concentration of proteins.
- Mitochondria, to provide ATP for protein synthesis and other cell activities.

The figure (right) is an electron micrograph of a pancreas cell and shows these distinctive features.

## CONTROL OF GASTRIC JUICE SECRETION

The control of digestive juice secretion involves both nerves and hormones. The control of gastric juice secretion is described here as an example.
Before food reaches the stomach, gastric juice is already being secreted, as a result of a reflex action. The sight or smell of food stimulates the brain to send nerve impulses to exocrine gland cells in the wall of the stomach. The gland cells start to secrete gastric juice in response.
Much more gastric juice is secreted when food enters the stomach. The food is detected by touch receptors and chemoreceptors in the lining of the stomach and by stretch receptors in the stomach wall. Impulses are sent from these receptors to the brain, which sends more nerve impulses to the exocrine gland cells.
When food is in the stomach, impulses are also sent to endocrine gland cells in the stomach lining that secrete a hormone called gastrin. Gastrin is carried to the exocrine gland cells in the stomach wall, where it stimulates them to increase the secretion of hydrochloric acid. This causes the pH of the food that has entered the stomach to fall to about pH 3.0.

## MEMBRANE-BOUND DIGESTIVE ENZYMES

Enzymes secreted by exocrine gland cells become mixed with the food in the alimentary canal and carry out all the initial stages of digestion. However, some of the enzymes that complete the process of digestion work in a different way. They are produced by the wall of the small intestine, but are not secreted. Instead, these enzymes remain in the plasma membranes of cells on the surface of the villi (epithelium cells). The active sites of the enzymes are exposed to the food in the small intestine. They can digest their substrates and the products of digestion can then immediately be absorbed. Epithelium cells tend to be lost from the tips of villi by abrasion, but the membrane-bound enzymes continue to work as they become mixed into the food in the small intestine.

**Electron micrograph of an exocrine gland cell in the pancreas (× 6000).** The central region of one cell is shown including the nucleus.

# Digestive enzymes

## SOURCES OF DIGESTIVE ENZYMES

Food contains many different types of substance that have to be digested before they can be absorbed. Digestion therefore involves many different enzymes, secreted by exocrine glands. The table allows the contents of saliva, gastric juice and pancreatic juice to be compared – there are both similarities and differences.

| Digestive juice | Source | Content |
|---|---|---|
| saliva | salivary glands | – salivary amylase<br>– mucus |
| gastric juice | glands in stomach wall | – pepsinogen<br>– hydrochloric acid<br>– mucus |
| pancreatic juice | pancreas | – pancreatic amylase<br>– pancreatic lipase<br>– phospholipase<br>– trypsinogen<br>– carboxypeptidase<br>– $HCO_3^-$ ions (alkaline) |

Pepsin and trypsin are potentially very harmful to the exocrine gland cells that secrete them. They are therefore secreted as inactive precursors, called **pepsinogen** and **trypsinogen**. Pepsinogen is activated by hydrochloric acid, which converts it into pepsin. Different cells in the wall of the stomach secrete pepsinogen and hydrochloric acid (below). Pepsinogen is therefore only activated after it has been secreted. An enzyme, enterokinase, which is secreted by the lining of the small intestine, activates trypsinogen. Activation therefore only happens when trypsinogen enters the small intestine.

### Structure of the stomach wall
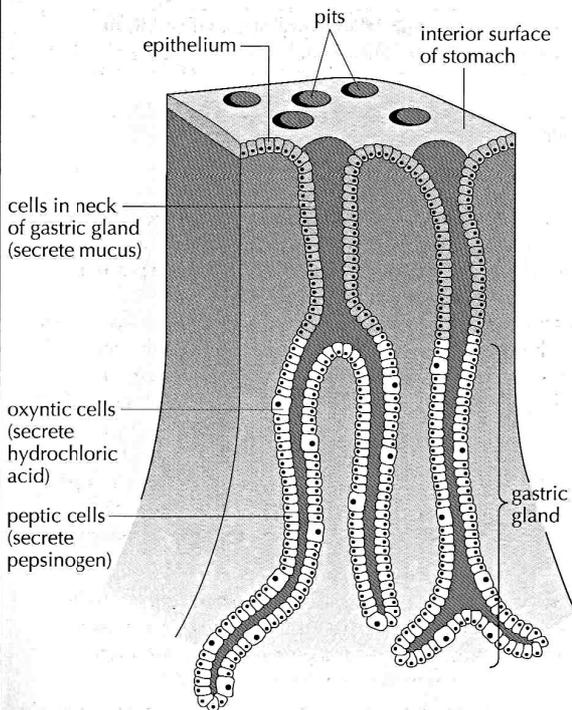


## DIGESTION OF LIPIDS

The digestion of lipids poses special problems, because they are insoluble in water. Foods and the digestive juices added to them are mainly composed of water. In the alimentary canal, lipids in foods melt and form liquid droplets. Because of their insolubility, these droplets tend to coalesce to form larger droplets.

Lipase is water-soluble so it does not enter the lipid droplets, but its active site is hydrophobic (shown on page 68) and hydrolyses lipids on the surface of droplets.

The droplets gradually decrease in size as the lipids on their surface are digested. However, food does not remain in the alimentary canal long enough for large droplets to be digested completely.

Bile helps to overcome this problem. It contains substances called **bile salts**, which are natural detergents. Bile salt molecules have a hydrophobic end and a hydrophilic end. They are therefore attracted to both water and lipids and coat lipid droplets, causing them to break up into smaller droplets. This process is called **emulsification**.

Bile is secreted by the liver and stored in the gall bladder. When it is discharged into the small intestine it emulsifies lipids, which speeds up their digestion, because many small droplets have a larger total surface area, accessible to lipase, than one large droplet of the same volume. With the help of bile, lipids can be completely digested in the small intestine.

## THE EFFECTS OF HELICOBACTER PYLORI

*Helicobacter pylori* is an acid-tolerant bacterium that infects the lining of the stomach. There is evidence that it causes several diseases of the stomach.

### 1. Stomach ulcers

These are areas of damage to the lining of the stomach. Old medical textbooks state that they are caused by excessive secretion of gastric juice, containing acid. There is now strong evidence that infection of the stomach with *H. pylori* is a more significant factor than gastric acid.

- Antacid treatments may relieve the symptoms of ulcers for a while, but not permanently.
- Antimicrobial treatments that eliminate *H. pylori* infection cure ulcers on a long-term basis.
- *H. pylori* infection is strongly associated with the presence of stomach ulcers.
- Voluntary infection with the bacterium has shown that it can cause gastritis, which often leads to ulceration.
- About half of the *H. pylori* strains isolated from patients with stomach disease produce toxins that cause inflammation – and patients infected with these strains tend to have the most severe ulceration.
- Proteases and other enzymes that are released by *H. pylori* damage the stomach lining.

### 2. Stomach cancer

Stomach cancer is the growth of tumours in the wall of the stomach. As with stomach ulcers, a far higher percentage of patients with stomach cancer are infected with *H. pylori* than the general population. *H. pylori* infection is associated with reduced vitamin C concentration in gastric juice. This will increase the chance of a tumour forming, but further research is needed to establish a causal link between *H. pylori* infection and stomach cancer.

# Absorption of digested foods

## STRUCTURE OF THE ILEUM

Digested foods are absorbed in the small intestine, mainly in the latter part, called the **ileum**. The tissue layers of the wall of the ileum are shown in the transverse section below (left). These tissue layers are visible in the light micrograph of the ileum below (right).

Transverse section of ileum
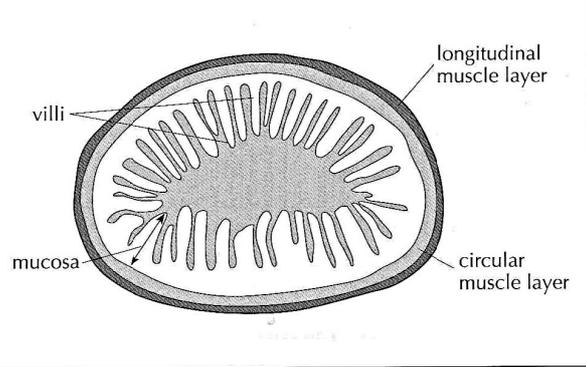


Micrograph of ileum in longitudinal section (× 40)
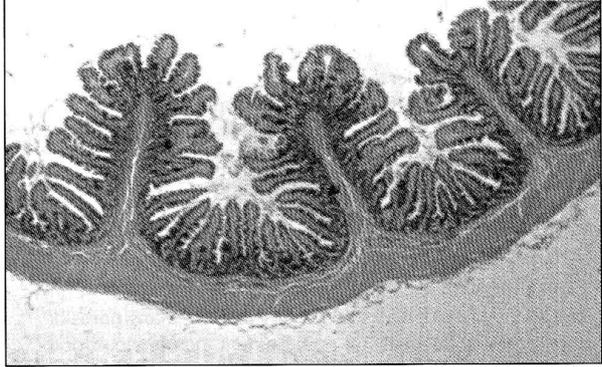


## VILLUS EPITHELIUM CELLS

Digested foods are absorbed by villi In the ileum. The structure of a villus is shown on page 47. The outer layer of cells where absorption occurs is the epithelium. The figure (right) is electron micrograph of epithelium cells, showing the structural features that are typical of this cell type. The plasma membranes of adjacent cells are firmly linked together near the free surface by structures called **tight junctions**. These structures prevent molecules from leaking between the epithelium cells. To be absorbed, digested foods have to pass through the plasma membrane of the epithelium cells, and absorption can therefore be carefully controlled. The table below describes the mechanisms used to absorb foods and the structural features used in these mechanisms.

Some materials are not absorbed, including cellulose, lignin, bile pigments, bacteria and abraded intestinal cells. They are therefore egested in the feces.

Micrograph of villus epithelium cells (× 2500)
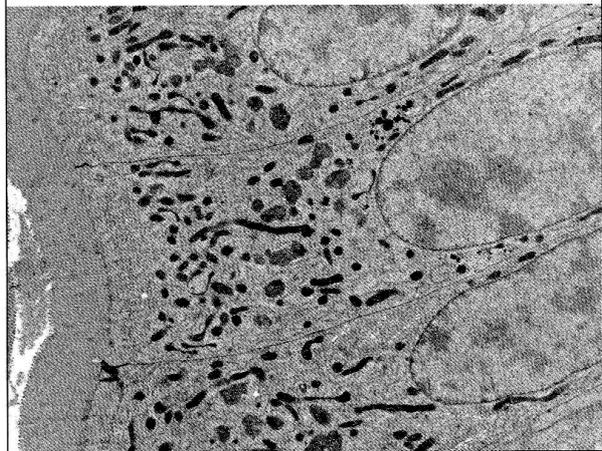


### Relationships between structure and function in villus epithelium cells

| Structural feature | Function |
| --- | --- |
| Microvilli – protrusions of the free surface of the plasma membrane into the lumen of the ileum; about 1 μm long and 0.1 μm wide. | Microvilli greatly increase the surface area of plasma membrane exposed to the digested food in the ileum. This increases the rate of absorption of foods by diffusion. Lipids, and other foods that can pass easily through the hydrophobic centre of the plasma membrane of the epithelium cells, are absorbed by **simple diffusion**. Fructose and some other hydrophilic food substances at a low concentration inside body cells are absorbed by **facilitated diffusion**. There is a steep enough concentration gradient for absorption of these substances by diffusion, but they need assistance to pass through the plasma membrane. Channel proteins help them to cross the hydrophobic centre of the membrane. |
| Mitochondria – there are many mitochondria scattered through the cytoplasm. | Mitochondria produce the ATP that is needed for absorption of substances by active transport. Pump proteins in the plasma membrane of the microvilli carry out the **active transport**. Glucose, amino acids and mineral ions including sodium, calcium and iron are absorbed in this way. |
| Pinocytic vesicles – there are many small vesicles, especially near the microvilli. | Pinocytic vesicles are formed by **endocytosis**. Each vesicle contains a small droplet of fluid from the lumen of the ileum. The membranes of these vesicles are formed from the plasma membrane and so contain channels for facilitated diffusion and pumps for active transport. Digested foods can be absorbed from the vesicles into the cytoplasm. |

# HL Liver

## BLOOD FLOW THROUGH THE LIVER

The liver is the largest organ in the human abdomen. It contains huge numbers of cells called hepatocytes, which carry out many vital processes. The liver is supplied with blood by two vessels – the **hepatic portal vein** and the **hepatic artery**. One vessel, the **hepatic vein**, carries blood away. The blood brought by the hepatic portal vein is deoxygenated, because it has already flowed through the wall of the stomach or the intestines. The level of nutrients in this blood varies considerably, depending on the amount of digested food that is being absorbed. One of the main functions of the liver is to regulate levels of nutrients before the blood flows on to the rest of the body. Excessively high levels of glucose and other nutrients would cause damage to the organs of the body, especially the brain.

Inside the liver, the hepatic portal vein divides up into vessels called **sinusoids**. These vessels are wider than normal capillaries, with walls that are more porous. The walls consist of a single layer of very thin cells. There are many pores or gaps between the cells but no basement membrane. Blood flowing along the sinusoids is therefore in close contact with the surrounding hepatocytes.

The hepatic artery supplies the liver with oxygenated blood from the left side of the heart via the aorta. Branches of the hepatic artery join the sinusoids at various points along their length, providing the hepatocytes with the oxygen that they need for aerobic cell respiration.

The sinusoids drain into wider vessels that are branches of the hepatic vein. Blood from the liver is carried by the hepatic vein to the right side of the heart via the inferior vena cava. The figure (below) shows the relationships between blood vessels in liver tissue.

### Structure of a sinusoid in the liver



branch of hepatic portal vein

branch of hepatic artery

single layer of cells forming the wall of the sinusoid

hepatocytes

lumen of sinusoid

Kupffer cell

branch of hepatic vein
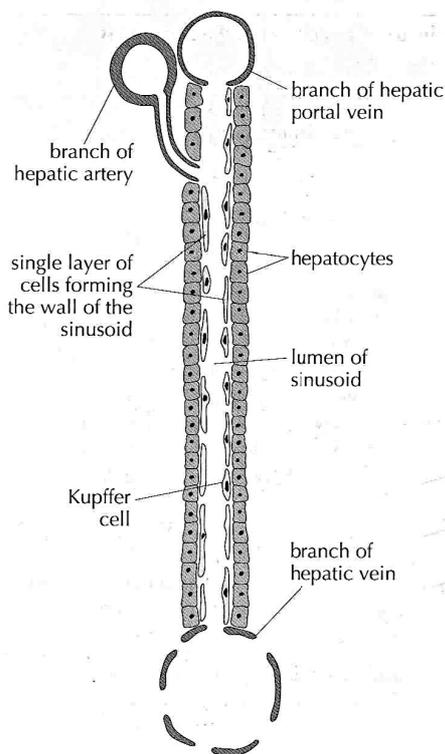
## ROLES OF THE LIVER

### Nutrient storage and regulation

When certain nutrients are in excess in the blood, hepatocytes absorb and store them, releasing them when they are at too low a level. For example, when the blood glucose level is too high, insulin stimulates hepatocytes to absorb glucose and convert it to glycogen for storage. When the blood glucose level is too low, glucagon stimulates hepatocytes to break down glycogen and release glucose into the blood. Iron, retinol (vitamin A) and calciferol (vitamin D) are also stored in the liver when they are in surplus and released when there is a deficit in the blood. Negative feedback

### Breakdown of erythrocytes

Erythrocytes, also called red blood cells, have a fairly short lifespan of about 120 days. The plasma membrane becomes fragile and eventually ruptures, releasing the hemoglobin into the blood plasma. The hemoglobin is absorbed by **phagocytosis**, chiefly in the liver. Some of the cells in the walls of the sinusoids are phagocytic, called **Kupffer cells**. Inside these cells the hemoglobin is split into heme groups and globins. The globins are hydrolysed to amino acids, which are released into the blood. Iron is removed from the heme groups, to leave a yellow coloured substance called bile pigment or bilirubin. The iron and the bile pigment are released into the blood. Much of the iron is carried to bone marrow, to be used in production of hemoglobin for new red blood cells. The bile pigment is used for bile production in the liver.
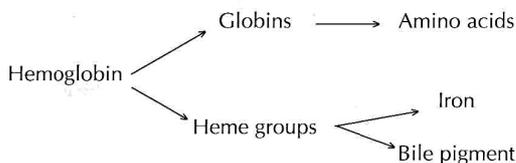


### Synthesis of plasma proteins

The rough endoplasmic reticulum of hepatocytes produces 90% of the proteins in blood plasma, including all of the albumin and fibrinogen.

### Synthesis of cholesterol

Although some cholesterol is absorbed from food in the intestine, a larger quantity is synthesized each day by hepatocytes.

### Detoxification

Hepatocytes absorb toxic substances from blood and convert them by chemical reactions into non-toxic or less toxic substances.

## LIVER DAMAGE FROM ALCOHOL ABUSE

Liver cells absorb alcohol and convert it into other substances to detoxify it. Excessive consumption of alcohol therefore damages liver cells more than most other parts of the body. Fatty deposits build up, which can cause hepatitis. Alcoholic hepatitis is inflammation of the liver, often associated with nausea and jaundice. If this is persistent (chronic), for example after ten or more years of heavy drinking, it can cause cirrhosis – normal liver tissue is gradually replaced by scar tissue. Liver cells gradually die and are not replaced, so liver function becomes increasingly poor and eventually death can result from liver failure.

# ⓗⓛ Cardiac cycle

## EVENTS OF THE CARDIAC CYCLE

The sequence of actions occurring repeatedly in a beating heart is called the cardiac cycle. The cardiac cycle is described briefly on page 48. The figure below shows the pressure and volume changes in the left atrium, left ventricle and aorta, during two cycles. It also shows electric currents (electrocardiogram) and sounds (phonocardiogram) generated by the beating heart.
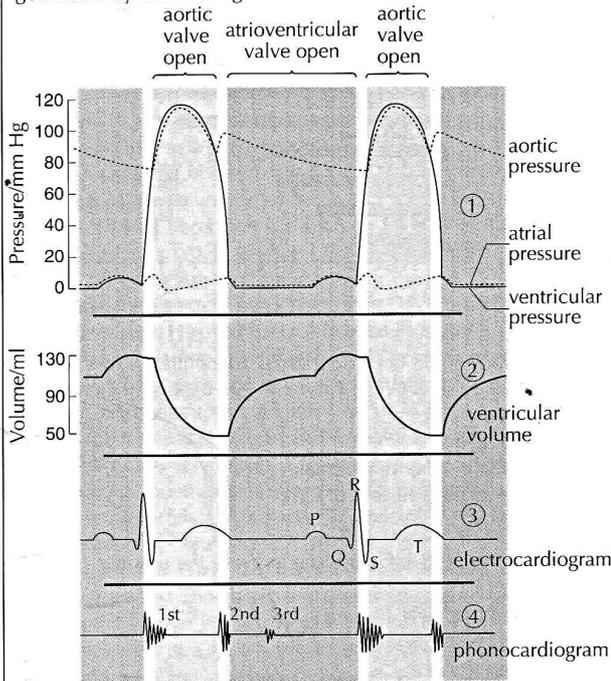


Contraction of the chambers of the heart is called **systole** and relaxation is called **diastole**.

### 1. Atrial systole
The cardiac cycle begins with the contraction of the wall of the atrium. This happens when the ventricle is already 70% full. The contraction of the atrium pumps more blood into the ventricle, filling it to its maximum capacity before the start of ventricular systole.

### 2. Ventricular systole
Contraction of the ventricle wall causes a rapid increase in pressure inside the ventricle. This causes the closure of the atrio-ventricular valve, with resulting vibrations in the valve and adjacent walls of the heart. These vibrations are the first heart sound. The pressure in the ventricle rapidly rises above the pressure in the aorta, causing the aortic (semi-lunar) valve to open. Blood can then be pumped from the ventricle into the aorta, raising the aortic blood pressure and decreasing the volume of blood in the ventricle to a minimum. While the ventricle is contracting, the atrium is relaxing and blood enters it from the pulmonary veins.

### 3. Ventricular diastole
Relaxation of the ventricle wall causes pressure in the ventricle to fall below the pressure in the aorta. The semi-lunar valve therefore closes, with the resulting vibrations that are the cause of the second heart sound. When the pressure in the ventricle falls below the pressure in the atrium, the atrio-ventricular valve opens and blood that has accumulated in the atrium flows into the ventricle causing a rapid rise in ventricular volume. With both the atrium and the ventricle relaxed, blood continues to drain from the pulmonary veins through the atrium into the ventricle until by the end of the cycle it is about 70% full.

## CONTROL OF THE HEART BEAT

Heart muscle cells are stimulated to contract by electrical impulses. Interconnections between adjacent cells allow impulses to spread through the wall of the heart, stimulating it to contract. A small region in the wall of the right atrium initiates each impulse (right). This region is called the SA node (sinoatrial node) and acts as the pacemaker of the heart. Impulses initiated by the SA node spread out in all directions through the walls of the atria, but are prevented from spreading directly into the walls of the ventricles by a layer of fibrous tissue. Instead, impulses have to travel to the ventricles via a second node, called the AV node (atrioventricular node). This node is positioned in the wall of the right atrium, close to the junction between the atria and ventricles. Impulses reach the AV node 0.03 seconds after being emitted from the SA node. There is a delay of 0.09 seconds before impulses pass on from the AV node, which gives the atria time to pump blood into the ventricles before the ventricles contract. Impulses are sent from the AV node along two bundles of conducting fibres that pass through the septum between the left and right ventricles, to the base of the heart. Narrower conducting fibres branch out from these bundles and carry impulses to all parts of the walls of the ventricles, causing almost simultaneous contraction throughout the ventricles. The effects of nerves and hormones on the heart beat rate are described on page 48.

**Structures involved in the control of the heart beat**
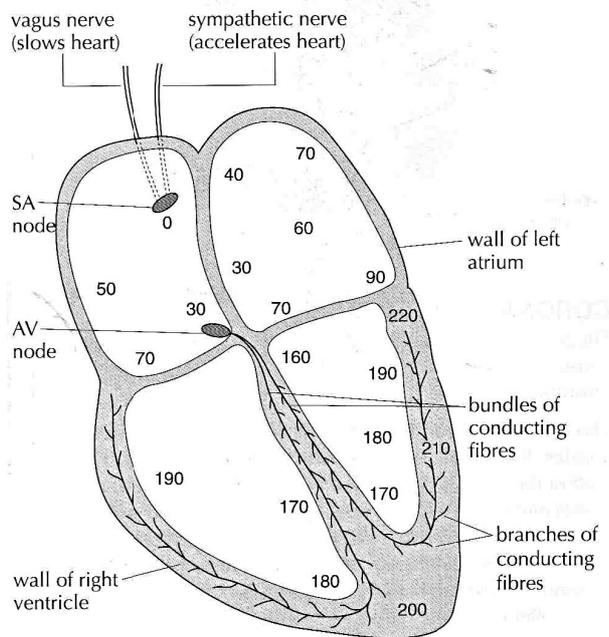


Numbers represent the time taken for impulses from the pacemaker to reach different parts of the heart wall

# Coronary heart disease

## ATHEROSCLEROSIS

Atherosclerosis is a degenerative disease of large and medium sized arteries. Phagocytes are attracted to sites of damage to the inner lining of the arteries. The phagocytes release growth factors that stimulate the muscle and fibrous tissues in the artery wall to thicken. LDL may penetrate the damaged areas and release cholesterol, which can build up to form large deposits. The growth of wall tissue and accumulation of cholesterol cause the artery wall to bulge inwards, reducing or even preventing the flow of blood. The thickened wall loses its elasticity and calcium salts are sometimes deposited in it, making it hard.

The figure (below) shows a healthy coronary artery and another that shows signs of atherosclerosis.
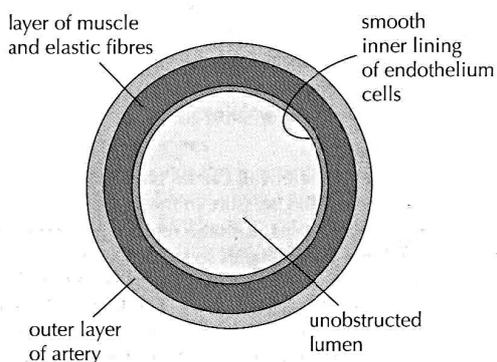


**Structure of an artery showing atherosclerosis**
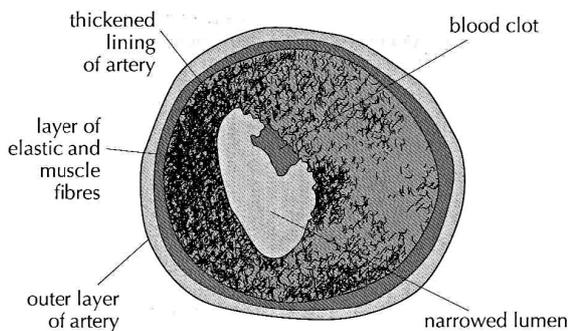


## CORONARY THROMBOSIS

The rough inner surface of atherosclerotic arteries tends to cause blood clots to form. The formation of clots is called thrombosis.

The wall of the heart is supplied with blood by the coronary arteries. If a blood clot blocks one of these arteries, part of the wall of the heart is deprived of its supply of oxygen. The cells in this part of the wall are unable to respire and so stop contracting. This is either called myocardial infarction or a heart attack. Sometimes small, uncoordinated contractions continue. These are called fibrillations, but they do not pump blood effectively.

## FACTORS AFFECTING THE RISK OF CHD

Atherosclerosis and coronary thrombosis are together known as coronary heart disease (CHD). The rates of CHD vary widely between countries.
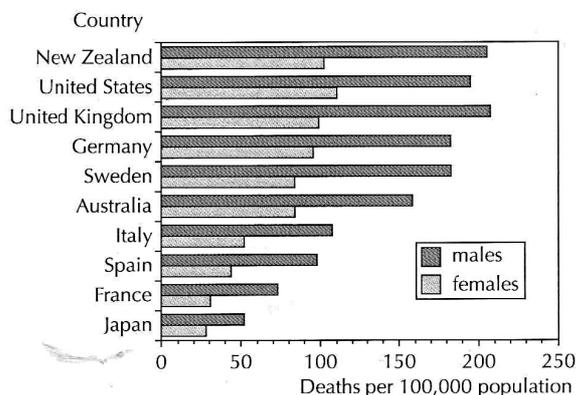


Much research has been done to try to identify factors that increase the risk of CHD. The following factors all increase the statistical risk:
• Increasing age
• Being male rather than female
• Having a family history of CHD

These three factors are not influenced by a person's lifestyle, but some of lifestyle factors that increase the risk are:
• Obesity
• Physical inactivity
• High blood pressure
• Tobacco smoking

The effect of diet is more equivocal. There is some evidence for dietary factors increasing the risk of CHD:
• Trans fat – positively correlated with CHD rates and the data is difficult to explain in any way other than that trans fats cause CHD
• Saturated fat intake – positively correlated with CHD rates in some countries, but evidence of a causal link is lacking.
• Cholesterol intake – reducing dietary cholesterol tends to reduce blood cholesterol levels slightly, and there is a positive correlation between blood cholesterol levels and CHD, but it is a weaker correlation than with saturated fat, and again the causal link is not proven. Cholesterol in blood can be part of both low-density and high-density lipoprotein (LDL and HDL). Whereas high LDL levels are associated with an increased risk of CHD, high HDL levels are associated with a reduced risk. This is because HDL is used to remove cholesterol from tissues.

The levels of LDL, HDL and saturated fats in the blood are not solely due to diet – genetic factors are also important. This may explain why some populations consume large quantities of cholesterol and saturated fats and yet have extremely low CHD rates –the Maasai of Kenya for example.

Finally, there have been claims that some factors reduce the risk of CHD. An example is cis-unsaturated fatty acid intake. These fatty acids are found in olive oil and may explain low CHD rates in Mediterranean countries. However, more evidence is needed before a causal link is established.

# Oxygen transport

Oxygen is transported from the lungs to respiring tissues by hemoglobin in red blood cells. Hemoglobin is a protein that is highly adapted to its function.

## OXYGEN DISSOCIATION CURVES

If air with the normal oxygen content is bubbled through a sample of blood, oxygen binds to the hemoglobin until almost all of the hemoglobin molecules have four oxygen molecules bound. The hemoglobin is nearly 100% saturated. If air with a low oxygen content is then bubbled through, some of the oxygen dissociates from the hemoglobin, reducing its percentage saturation. The oxygen content of the air is measured as a **partial pressure**. *Partial pressures are the pressures exerted by each of the gases in a mixture of gases.* The percentage saturation of hemoglobin with oxygen at each partial pressure of oxygen is shown on an oxygen dissociation curve. The figure (below) shows the oxygen dissociation curves of hemoglobin and myoglobin.

Myoglobin is a protein consisting of one globin and one heme group that is used to store oxygen in muscles. The oxygen curve for myoglobin is to the left of the curve for adult hemoglobin because myoglobin has a higher affinity for oxygen. At moderate partial pressures of oxygen, adult hemoglobin releases oxygen and myoglobin binds it. Myoglobin only releases its oxygen when the partial pressure of oxygen in the muscle is very low. The release of oxygen from myoglobin delays the onset of anaerobic respiration in muscles during vigorous exercise.

The dissociation curves for myoglobin and hemoglobin have different shapes. The curve for hemoglobin is S-shaped and that for myoglobin is not. Myoglobin consists of one heme group attached to a globin, whereas hemoglobin has four heme groups, each attached to different globins that interact with each other. As oxygen molecules dissociate from hemoglobin, conformational changes occur, which make it easier for other oxygen molecules to dissociate. Blood containing adult hemoglobin therefore releases large amounts of oxygen over a narrow range of oxygen partial pressures, corresponding to the conditions normally found in respiring tissues.

**Oxygen dissociation curves of hemoglobin and myoglobin**
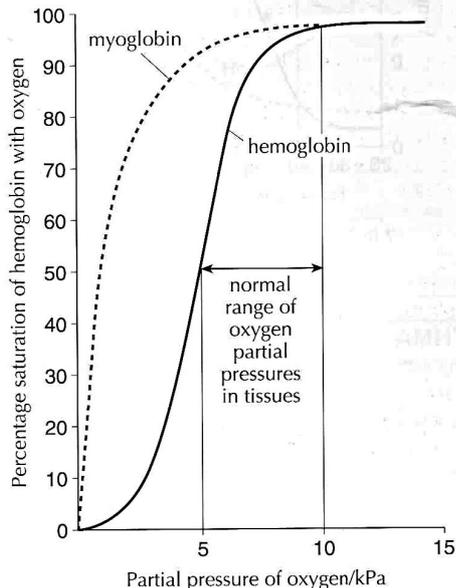


## THE BOHR SHIFT

The release of oxygen by hemoglobin in respiring tissues is promoted by an effect called the Bohr shift. Hemoglobin's affinity for oxygen is reduced as the partial pressure of carbon dioxide increases (below). Respiring tissues have high partial pressures of carbon dioxide, so oxygen tends to dissociate. The lungs have lower partial pressures of carbon dioxide, so oxygen tends to bind to hemoglobin.

**Effect of $CO_2$ on the oxygen dissociation curve of hemoglobin**
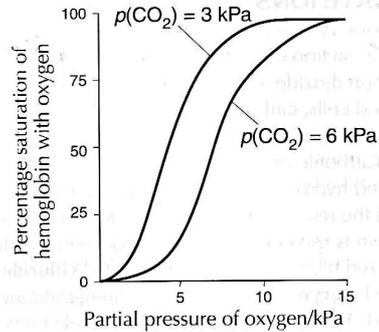


## FETAL HEMOGLOBIN

The hemoglobin in the red blood cells of a fetus is slightly different in amino acid sequence from adult hemoglobin. The figure (below) shows that it has greater affinity for oxygen and so, in the placenta, the oxygen that dissociates from adult hemoglobin binds to fetal hemoglobin, which only releases it once it enters the tissues of the fetus.

**Oxygen dissociation curves of adult and fetal hemoglobin**
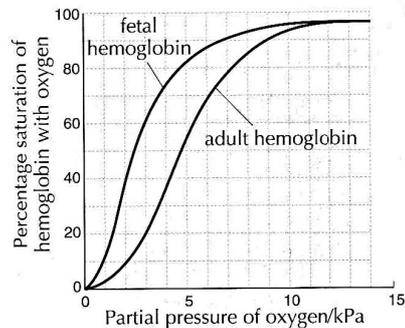


## GAS EXCHANGE AT HIGH ALTITUDE

The partial pressure of oxygen at high altitude is lower than at sea level. Hemoglobin may not become fully saturated as it passes through the lungs, so tissues of the body may not be adequately supplied with oxygen. A condition called mountain sickness can develop, with muscular weakness, rapid pulse, nausea and headaches. This can be avoided by ascending gradually to allow the body to acclimatize to high altitude. During acclimatization the ventilation rate increases. Extra red blood cells are produced, increasing the hemoglobin content of the blood. Muscles produce more myoglobin and develop a denser capillary network. These changes help to supply the body with enough oxygen. Some people who are native to high altitude show other adaptations, including a high lung capacity with a large surface area for gas exchange, larger tidal volumes and hemoglobin with an increased affinity for oxygen.

# Carbon dioxide transport

Carbon dioxide is produced by aerobic respiration in cells and then either diffuses directly into capillaries or into tissue fluid that is drawn into capillaries. Carbon dioxide is carried by the blood to the lungs in three different ways. A small amount (7%) is carried dissolved in the plasma. The remainder is either converted to hydrogen carbonate ions or binds to hemoglobin.

## CONVERSION TO HYDROGEN CARBONATE IONS

Carbon dioxide can be converted into hydrogen carbonate ions within a fraction of a second of entering the blood. About 70% of carbon dioxide is carried in this way. After diffusing into red blood cells, carbon dioxide combines with water to form carbonic acid. This reaction is catalysed by carbonic anhydrase. Carbonic acid rapidly dissociates into hydrogen carbonate and hydrogen ions. The hydrogen carbonate ions move out of the red blood cells by facilitated diffusion. A carrier protein is used that simultaneously moves a chloride ion into the red blood cell. This is called the **chloride shift** and prevents the balance of charges across the membrane from being altered. The figure (below) shows the reactions that produce hydrogen carbonate ions and the chloride shift. The hydrogen ions that dissociate from carbonic acid bind to hemoglobin in the red blood cells, preventing an excessive change in pH. This is called pH buffering. Plasma proteins also act as pH buffers in blood.
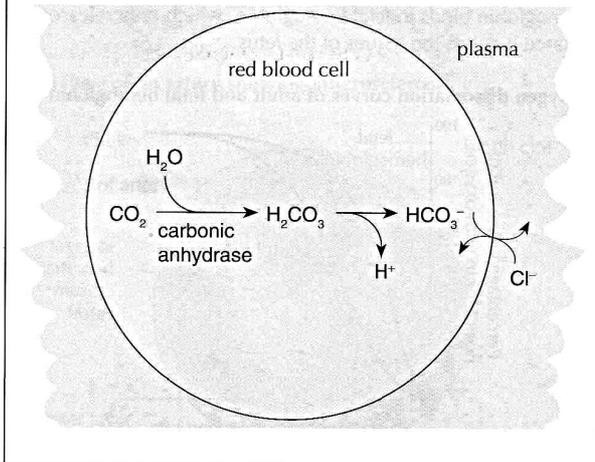


## BINDING OF CARBON DIOXIDE TO HEMOGLOBIN

In respiring tissues, carbon dioxide binds reversibly to hemoglobin, to form carbaminohemoglobin.
In the lungs, **carbaminohemoglobin** dissociates and the carbon dioxide is released. Between 15% and 25% of carbon dioxide is carried in this way. The binding of carbon dioxide and hydrogen ions to hemoglobin lowers its affinity for oxygen. This causes the Bohr shift (page 169).

## THE EFFECT OF EXERCISE ON VENTILATION

During vigorous exercise, the energy demands of the body can increase by over ten times. The rate of aerobic respiration in muscles rises so there is an increase in the amount of $CO_2$ entering the blood and the concentration rises. This reduces the pH of the blood and is rapidly detected by cells in the walls of arteries, which monitor blood pH and concentrations of oxygen and carbon dioxide in the blood. These cells are called **chemosensors**. The chemosensors send nerve impulses to the parts of the medulla of the brain that control the ventilation rate, called the **breathing centres**. The breathing centres also monitor blood pH and carbon dioxide concentration. If the concentration of carbon dioxide in the blood rises and the blood pH falls below its normal level of pH 7.4, the breathing centres increase the rate of inspiration and expiration. This is done by sending nerve impulses to the diaphragm and intercostal muscles, causing them to increase the rate at which they contract and relax. The increase in the ventilation rate helps to remove from the body the $CO_2$ produced in aerobic cell respiration. It also helps to increase the rate of oxygen uptake, which allows aerobic cell respiration to continue in the muscles and it helps to repay the oxygen debt after anaerobic cell respiration.
After exercise, the level of $CO_2$ in the blood falls, the pH of the blood rises and the breathing centres cause the ventilation rate to decrease.
The figure (below) shows the relationship between blood pH, partial pressure of carbon dioxide in blood and ventilation rate.

**Effect of varying blood pH and $CO_2$ level on the ventilation rate**
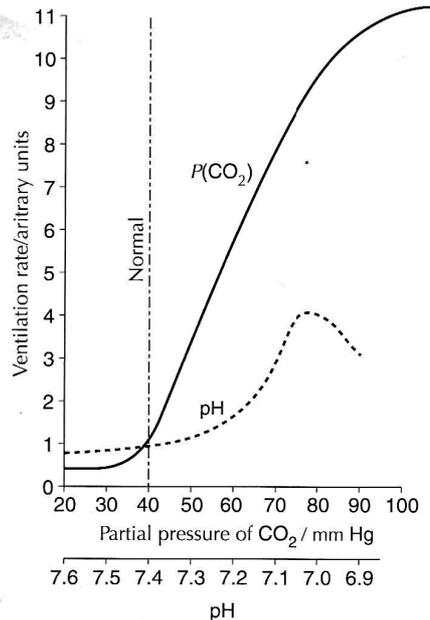


## ASTHMA

During asthma attacks the muscles in the wall of the bronchi contract excessively, narrowing the bronchi. Ventilation is a struggle and gas exchange is reduced.
Asthma is an allergic reaction, often to house dust mites, but sometimes also to pollen, pets and some fungi. According to a recent theory, living in very clean homes increases the risk. Without enough pathogens to fight, the immune system starts to react against harmless substances, causing allergies to develop.

# EXAM QUESTIONS ON OPTION H – FURTHER HUMAN PHYSIOLOGY

H1 The bacterium *Helicobacter pylori* infects the lining of the stomach. A survey was done using patients who had complained of pain or discomfort in their digestive system. The lining of their oesophagus, stomach and duodenum (upper part of the small intestine) was examined using an endoscope and the patients' blood was tested for the presence of antibodies against *H. pylori*.

The table below show the results of the survey.

| Endoscopy finding | Antibodies against *H. pylori* present (number of patients) | Antibodies against *H. pylori* absent (number of patients) |
|---|---|---|
| Normal | 51 | 82 |
| Oesophagus inflamed | 11 | 25 |
| Stomach ulcer | 15 | 2 |
| Stomach cancer | 5 | 0 |
| Duodenum inflamed | 15 | 2 |
| Duodenal ulcer | 24 | 1 |

a) Explain why the researchers tested for antibodies against *H. pylori* in the blood of the patients. [2]

b) Discuss the evidence from the survey results for *H. pylori* as a cause of stomach ulcers and stomach cancer. [3]

c) (i) Compare the results for inflammation of the oesophagus and the duodenum. [2]

   (ii) Suggest a reason for the difference in the results. [2]

H2 a) Outline how the atria of the heart are stimulated to contract. [2]

b) Explain the origin of the heart sounds. [2]

H3 $V_E$ is the total volume of air expired from the lungs per minute. The graph below shows the relationship between $V_E$ and the carbon dioxide content of the inspired air.
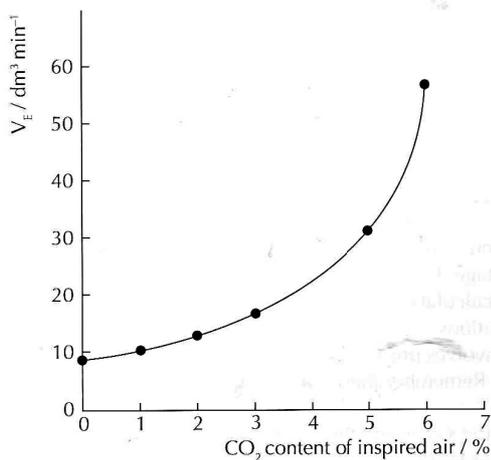


a) Outline the relationship between the carbon dioxide content of inspired air and $V_E$. [2]

b) Explain how the carbon dioxide content of inspired air can affect $V_E$. [3]

c) Predict the effect on $V_E$ of increasing the carbon dioxide concentration of inspired air above 7%. [2]

If you want to do well in your final exams, you must prepare for them very carefully in the weeks beforehand.

The most important task is to memorize all the facts that you have been taught. For a high grade, you will need a comprehensive knowledge of them. You will need to spend many hours on revision and find tactics that work for you.

You should also practise answering exam questions. You can use the questions at the end of topics in this book, after you have revised each topic. Your teacher should also give you some past exam papers to try.

There are three styles of question in IB Biology exams.

- **Multiple choice questions** – These are questions where you choose one of four possible answers. Read all of them before choosing one. If you cannot decide on one answer, try to eliminate answers that are obviously wrong to narrow down the possibilities. Leave difficult questions until you have answered the straightforward ones. Give an answer to every question – marks are not deducted for wrong answers.

- **Structured questions** – These questions are broken up into small sections, each of which you answer in the space or on the lines provided. If you run out of space, continue your answer elsewhere on the paper – it will be marked as long as you indicate clearly what you have done. The number of marks for each section is indicated and this helps show you how detailed your answer needs to be. Some structured questions involve data analysis. Look through the data questions in this book to see some of the ways in which data can be presented. You should always study the data very carefully before answering the questions, for example the scales and labelling on the axes of graphs. If there are calculations, remember to show your working and give units with your answer, for example grams or millimetres.

- **Free response questions** – These questions require long and detailed answers on lined paper. You can decide what style of answer to give. Usually continuous prose is best, but sometimes ideas can be shown on a table or on a carefully annotated diagram. There may be a choice of free response question. Read the whole of each question before making your choice.
  There will be marks for the quality of construction of your answer. If the question is divided up into sections (a), (b) and so on, you must answer it in these sections. Try to express your ideas clearly so that the examiner understands what you mean. Plan out your answer on scrap paper, so that you arrange your ideas in a logical sequence and do not include irrelevant material.
  As with all questions, you must write legibly or the examiner may not be able to mark your work. This may mean that you have to write more slowly than normal.

If you do revise carefully and build up a comprehensive knowledge of the facts on the syllabus you should find many of the questions straightforward. This is because, in IB Biology exams, 50% of the marks are for simple factual recall. These questions will start with words like *list, state, outline* or *describe*. The other 50% of the marks involve more than simple factual recall – they involve expressing ideas that are more complex or involve using your knowledge to develop an answer that you probably haven't been taught.

The word at the start of each question tells you what to do. These words are therefore called command terms.

*Explain* – Sometimes this involves giving the mechanism behind something – often a logical chain of events, each one causing the next. This is a 'how' sort of explanation. A key word is often 'therefore'. Sometimes it involves giving the reasons or causes for something. This is a 'why' sort of explanation. A key word is often 'because'.

*Discuss* – There won't be a simple straightforward answer to these questions. Sometimes your answer should include arguments for and against something. Try to give a balanced account. Sometimes your answer should consist of a series of alternative hypotheses – you could indicate how likely each one is but you don't need to make a final choice.

*Suggest* – Don't expect to have been taught the answer to these questions. Use your overall biological understanding to find answers – as long as they are possible, they will get a mark.

*Compare* – This type of question involves assessing how similar or different two or more things are. You cannot do this by describing the things separately. Every point that you make should be a similarity or a difference. There may be more similarities or more differences – all of them are relevant.

*Distinguish* – This is similar to a compare question, except that only differences need to be included in your answer. The key word in this type of question is often 'whereas'.
In both compare and distinguish questions a table is often the best way to arrange your answer. Use the columns of the table for the things that you are comparing and the rows for the individual similarities or differences.

*Evaluate* – This usually involves assessing the value, importance or effects of something. You might have to assess how useful a technique is, or how useful a model is in helping to explain something. You might have to assess the expected impacts of something on the environment. Whatever it is that you are evaluating, you will probably have to use your judgement in composing your answer.

There are other command terms that are used in questions, but they are more straightforward and you are unlikely to have difficulty in understanding what sort of answer to give.

## TOPICS 1 AND 2 STATISTICAL ANALYSIS AND CELLS

1 (a) X = rough endoplasmic reticulum  Y = mitochondria  (b) nuclear membrane is the curved structure on the left-hand side (c) proteins because there is rough endoplasmic reticulum with ribosomes which make protein; ATP because there are many mitochondria which make ATP.

2 (a)(i) phospholipid (ii) head is hydrophilic and tails are hydrophobic (b)(i) II is integral (ii) any two of: III is a pump protein; transfers specific substances; uses energy from ATP to move substance against the concentration gradient.

3 (a)(i) 12.4; %; (ii) 5.22 (b)(i) positive; correlation; (ii) does not prove obesity causes high blood pressure; correlation does not establish a causal relationship; high blood pressure may be caused by something else that also caused obesity;

## TOPIC 3 THE CHEMISTRY OF LIFE

1 (a)(i) DNA (ii) DNA (iii) RNA (b) experimental error (c)(i) DNA is double stranded; A pairs with T and C pairs with G; one base in each pair is therefore A or G, so A + G = 50%;  (ii) any two of A = T; C = G; C + G = 50%; A + G / C + G = 1.00 (d)(i) influenza virus (ii) RNA contains uracil instead of thymine; single stranded so amounts of G and C not equal.

2 (a)(i) $CO_2$ concentration falls in the light and rises in the dark; (ii) $CO_2$ concentration falls when it is warmer and rises when it is cooler; (b) $CO_2$ concentration is more closely related to light intensity; when there is a temporary dark period during the third day but it stays warm pH drops so $CO_2$ concentration rises; (c)(i) respiration producing $CO_2$; (ii) photosynthesis causing $CO_2$ uptake;

3 (a) radical/variable portion of the amino acid (b) C – N bond; O= linked to C and H- linked to N (c) 70S ribosomes in prokaryotes vs. 80S ribosomes in eukaryotes; free ribosomes in prokaryotes vs. ribosomes sometimes linked to rough endoplasmic reticulum in eukaryotes.

## TOPIC 4 GENETICS

1 (a) O group individual must be genotype ii because it is due to a recessive allele; B group individual in generation 2 must be $I^Bi$ because the parent that was blood group A could not have passed on $I^B$; B group individual in generation 3 must have been $I^Bi$ because the O group parent must have passed on i;
(b) parents could have been group O; parents could have been group A with genotype $I^Ai$; parents could have been group B with genotype $I^Bi$ (c) blood transfusion.

2 (a) $C^r C^r$  $C^W C^W$ and $C^r C^W$ (b) The allele for red flowers is dominant in peas but codominant in *Mirabilis* (c) gametes $C^r$ and $C^W$; genotypes $C^r C^r$  $C^r C^W$  $C^W C^r$ and $C^W C^W$; phenotypes red pink pink and white, respectively.

3 (a) a group of organisms with identical genotypes (b) nucleus removed from a cell in an adult organism; nucleus removed from an egg cell and replaced with the nucleus from the adult animal (c)(i) fragments had moved down; larger fragments are nearer the top and move more slowly; (ii) culture cells have the same profile as udder cells as they have the same pattern of bands; Dolly's blood cells have the same profile as the udder/culture cells as they have the same pattern of bands; Dolly was cloned from the udder cells; sheep 1–12 are genetically different;

## TOPIC 5 ECOLOGY AND EVOLUTION

1 (a) sigmoid/S-shaped (b)(i) line reaching a plateau by year 8 (ii) any two of: food supply; predation; breeding sites; disease (c)(i) population would have reached carrying capacity more quickly (ii) carrying capacity would have been the same.

2 (a) I = secondary consumers II = primary consumers III = producers (b) chemical energy (c) arrow from the sun to box III (d) any two of: arrows represent energy losses; heat produced because energy transformations are never 100% efficient; energy not passed along the food chain to another organism.

3 (a) methane causes an increase in the Earth's temperature by the greenhouse effect; temperature only increases as a result of an increase in atmospheric methane; methane emissions to the atmosphere must be greater than losses (b) methane emission is a natural process, e.g. swamps and marshes; humans cause methane emission, e.g. coal burning/cattle and sheep/rice paddies; most emissions are caused by humans/humans have increased emissions considerably (c) any three of: drain swamps and marshes; reduce cattle and sheep farming; stop growing rice in paddies; control releases of natural gas; reduce burning of coal; prevent forest fires/burning of biomass.

## TOPIC 6 HUMAN HEALTH AND PHYSIOLOGY

1 (a) $T_b$ is higher than $T_a$; $T_b$ is constant whereas $T_a$ is decreasing (b) heat absorbed from the environment; heat generated by cell respiration (c) active during darkness because it maintains constant high body temperature as a result of cell respiration.

2 (a)(i) ingestion of pathogens (ii) in blood; in body tissues (b) to allow the production of many different types of antibody; to fight many different diseases.

3 (a) I = trachea II = bronchioles (b) maintains concentration gradients of oxygen and $CO_2$ between air in alveoli and blood; ensures rapid diffusion/gaseous exchange (c) alveolus wall consisting of very thin cells; blood capillaries adjacent to alveolus; bronchiole connected to alveolus; diameter of alveolus indicated;

## TOPIC 7 NUCLEIC ACIDS AND PROTEINS

1 (a)(i) higher than 40 °C; initial rate was faster; then reaction stopped due to denaturation (ii) lower temperature than 40 °C because the rate is slower; 30 °C because the rate is half that at 40 °C (b)(i) curve drawn above the curve W (similar to curve Y) (ii) curve drawn above the curve W; gradient of curve decreasing markedly with time showing increasing inhibition as the substrate concentration falls.

2 (a) 3′ terminal is deoxyribose/ribose to which a nucleotide can be linked; 5′ terminal is phosphate group to which a nucleotide can be linked (b) Any 3 of : purines and pyrimidines are both bases; both are part of nucleotides; A and G are purines and C and T are pyrimidines; purines can only pair with pyrimidines in DNA; purines have two rings and purines only one ring (c) Any 5 of: DNA is transcribed; mRNA is translated; RNA is produced by transcription; polypeptides are produced by translation; transcription is done by RNA polymerase; translation is done by ribosomes;

3 (a) globular (b) number and sequence of amino acids (c)(i) X is a beta pleated sheet and Y is alpha helix (ii) hydrogen bonding (d) any two of: tertiary structure determines the enzyme's shape; determines the active site's shape; makes the enzyme substrate specific; shape ensures that when the substrate binds it is distorted/induced fit.

## TOPIC 8 CELL RESPIRATION AND PHOTOSYNTHESIS

1 (a) Any two of: double membrane; cristae/infoldings of inner membrane; ovoid shape; (b) double outer membrane shown; inner membrane shown folded in to form a crista (c)(i) label indicating the matrix (ii) label indicating the inner membrane/cristae (iii) label indicating the cytoplasm outside the mitochondria.

2 (a) peaks in the red and blue sections of the spectrum; minimum in the green section at about half of maximal rate (b) action and absorption spectra are closely correlated; because pigments absorb the light energy used in photosynthesis; the more light absorbed at a wavelength the more photosynthesis.

3 (a) oxidative phosphorylation and photophosphorylation (b) barrier to proton movement; allows a proton gradient to develop; location of ATP synthase; (c) plasma membrane;

## TOPIC 9 PLANT SCIENCE

1 (a)(i) more Pfr (ii) more Pfr (b) Pfr slowly reverts to Pr in darkness; timing is based on the amount of conversion; (c) Pfr promotes flowering in long-day plants; and inhibits it in short-day plants;

2 (a) Any three of: parallel versus net-like veins; vascular bundles distributed through stem versus in a ring; one versus two cotyledons; floral organs in 3s versus in 4s or 5s; unbranched versus branched roots; (b) apical meristem increases length of the stem; lateral meristem increases width of stem; (c) monocots cannot thicken their stems; cannot grow into large trees; less opportunity of branching;

3 (a)(i) 6 pm to 6 am/sunset to sunrise (ii) 6 am to 4.30 pm (b) CAM plant is the xerophyte because it opens its stomata at night; less water loss during cooler conditions in the night (c)(i) partial closure between 11 am and 12 am; followed by reopening (ii) plant needs to limit transpiration during the hottest part of the day.

## TOPIC 10 GENETICS

1 (a) polygenic (b) AaBb; blue-flowered (c) all gametes shown with one allele of each gene only; four homozygous genotypes shown AABB AAbb aaBB and aabb; four double heterozygous genotypes shown AaBb; eight other genotypes shown AABb AAbB aaBb aabB AaBB aABB Aabb and aAbb; all sixteen phenotypes indicated (d) 9 blue 3 red and 4 white (e) gene A converts white to red and gene B converts red to blue.

2 reassortment of genes into different combinations from those of the parents (b) black body long wing; grey body vestigial wing (c) genes are linked/found on the same chromosome; parental combinations are kept together; unless there is a cross-over between the genes (d) any two of: find which chromosome a gene is located on; identify all of the genes in a linkage group; estimate how far apart the loci of genes on a chromosome are.

3 (a) first; prophase; (b)(i) four chromatids (ii) five chiasmata; (c) breakage of chromatids; rejoining of non-sister chromatids; exchange of material between chromatids;

## TOPIC 11 HUMAN HEALTH AND PHYSIOLOGY

1 (a) excretion is removal from the body of waste products; waste products of metabolism (b) Any two of: protein in blood plasma but not urine; glucose in blood but not in urine; higher concentration of urea/waste products of metabolism in urine than blood plasma; composition of urine is more variable than blood plasma (c) loop of Henle makes medulla hypotonic by raising sodium/mineral ion concentration; allows production of hypertonic urine (d) basement membrane of glomerulus/filtration slits;

2 (a)(i) actin (ii) regions II and III (b)(i) II would increase in length (ii) I and III would increase in length.

3 (a) Any four of: both contain a haploid nucleus; both have a plasma membrane; the sperm has a tail but the egg does not; the egg has much more cytoplasm; mitochondria in sperm are helical but in eggs are ovoid; the egg has cortical granules but the sperm does not; (b) stimulates gametogenesis in both men and women; promotes development of follicles in women and primary spermatocytes in men; stimulates estrogen secretion in women but not testosterone in men; (c) both stimulate the development of the corpus luteum; both stimulate the secretion of progesterone; before fertilization by LH and after fertilization by HCG;

## OPTION A – HUMAN NUTRITION AND HEALTH

1 (a)(i) 24.3 (ii) 22.6 (b)(i) 24.2 and 22.5 (ii) values are very close (c) below 18.5 is underweight; 25–30 is overweight; above 30 is obese;

2 (a)(i) monounsaturated fatty acids have one double bond and polyunsaturated have more than one; (ii) trans fatty acids have hydrogen bonded to different sides of double bonded carbon atoms versus cis fatty acids have hydrogen bonded to the same side; (b) saturated fatty acids are linked with increased blood cholesterol; cholesterol/saturated fatty acids are linked with atheroma; correlation between saturated fat intake and CHD;

3 (a) one mark for any two of: protein; fats; carbohydrate; minerals; vitamins; water; (b) Any three of: human milk contains the ideal combination of nutrients for human babies; breast-feeding helps with bonding; breast milk contains antibodies; human milk does not cause allergies (c) milk production from cattle involves separating calves from their mothers when they are very young; also involves slaughter of calves/young cattle;

## OPTION B – PHYSIOLOGY OF EXERCISE

1 (a) humans store less oxygen per kg of body tissue (b) Any three of: both store most in blood; seal stores a higher proportion in blood than human; smallest proportion stored in lung of seal but muscle of human; human stores higher proportion in lung than seal; seal stores higher proportion in muscle than human (c) any three of: size of muscle; ratio of fast and slow fibres; concentration of myoglobin in muscle; amount of blood in muscle.

2 (a) thin actin and thick myosin filaments shown; actin filaments attached to Z discs; actin filaments interdigitating with myosin; (b) ATP provides energy; for myosin heads; to detach from actin and recock (c) cardiac output is higher when muscles are contracting;

3 (a) two; (b) discs bulge; soft pulpy core of disc is protruding; (c) (white matter of) spinal cord; (d) abnormal neck movements; heavy loads;

## OPTION C – CELLS AND ENERGY

1 (a) $CO_2$ concentration (b)(i) temperature; rate of photosynthesis rises as temperature rises; (ii) temperature controls the rate of photosynthesis between 35 and 40 °C; but is not the factor nearest to its minimum level/is supra-optimal (c) light is the limiting factor at low light intensity; temperature therefore does not affect the rate of photosynthesis.

2 (a) (i) malonate inhibits succinate dehydogenase/other example (ii) copper/mercury/silver ions/other example; (b) similarity: both types of inhibitor reduce the rate of catalysis; difference between competitive and non-competitive: inhibitor structure similar to substrate vs. not similar/inhibitor binds to active site vs. binds elsewhere.

3 (a) pyruvate; acetyl group; (b) both are $CO_2$; (c) NADH + H$^+$ (d) Krebs cycle;

## OPTION D – EVOLUTION

1 (a)(i) positive correlation (ii) any two of: primate brains are larger in relation to body mass; but there is much variation; largest primates have relatively small brains (iii) any two of: scattergram shows that human brain has the largest size; primates with a larger body mass have a smaller brain; human brain mass is furthest above the line of best fit (b) easier to climb trees/speed of movement/less food needed.

2 (a)(i) 2 (ii) 6 (iii) 9 (iv) 6 (v) 10 (vi) 7 (b) cladogram with four species; first split between rabbit and other three species; second split between lemur and other two species; final split between humans and orang utans;

3 (a) $p^2 + 2pq + q^2 = 1$ and $q^2$ is the frequency of homozygous recessives; frequency = 0.23/23% (b) 35% (c) carriers have increased resistance to malaria; selective advantage over homozygous dominants so the sickle cell allele survives.

## OPTION E – NEUROBIOLOGY AND BEHAVIOUR

1 (a) receptor protein; each receptor protein's shape is complementary to a specific odorant; (b) Any three of: G protein activates the enzyme adenylyl cyclase; enzyme converts ATP to CAMP; CAMP causes calcium channel to open; calcium causes chloride channel to open (c) membrane of chemoreceptor cell depolarizes/action potential created/chemoreceptor cell passes an impulse to a sensory neuron.

2 (a) photoreceptors (b) in sensory neurons from the retina to the brain; in motor neurons from the brain to the circular muscle fibres in the iris (c) no response when a light is shone into eye of unconscious patient indicates damage to the brainstem.

3 (a) supporting the hair cells/reticular lamina; (b)(i) three rows; small medium and longer stereocilia; arranged in a W shape; (ii) 1.2 μm; (iii) longer perceive lower frequency sounds; (c)(i) amplifies sounds; for the inner hair cells to perceive more easily; (ii) in the plasma membrane; mitochondria close to the edge of the cell;

## OPTION F – MICROBES AND BIOTECHNOLOGY

1 (a) bacteria numbers increase; bacteria use oxygen in aerobic cell respiration; (b) bacteria decompose raw sewage; ammonia and phosphate are released during decomposition; (c) ammonia is converted to nitrate; by nitrifying bacteria; (d) eutrophication; nutrients stimulate growth of photosynthetic bacteria/algae; (e) bacteria consumed by other organisms; raw sewage has all been decomposed;

2 (a) synthesis of DNA/cDNA; from RNA (b)(i) retroviruses (ii) HIV (c) any three of: mRNA can be obtained quite easily; genes can be hard to find; gene consisting of DNA can be made from RNA; no introns in the gene using reverse transcriptase; gene can be inserted into other organisms; cDNA/probes can be used to locate other genes;

3 (a)(i) protein coat/capsid (ii) nucleic acid/genes; (b) insert gene into viral DNA; virus acts as a vector for the gene; (c) intracellular; all viruses rely on a host cell for most of their processes;

## OPTION G – ECOLOGY AND CONSERVATION

1 (a)(i) S. marcescens feeds on the nutrients so more grow at high nutrient levels (ii) C. striatum reduce the numbers by predation (iii) D. nasutum increases the numbers because it feeds on C. striatum; which reduces the predation of S. marcescens (b) low population of S. marcescens at low nutrient levels; therefore very low levels of C. striatum on which D. nastum feeds (c) longer food chain with higher nutrient levels.

2 (a) indicator species need particular environmental conditions; can be used to give a measure of pollution levels/levels of an environmental variable (b) any two of: captive breeding and release of endangered species; growth of endangered plants in botanic gardens; storage of frozen seeds of endangered species in seed banks.

3 (a) mercury inputs reduced; (b) increases/decreases when river flow rates rise/fall; high rainfall leaches more mercury out; (c) death of organisms in higher trophic levels; toxic effects for humans consuming fish from higher trophic levels;

## OPTION H – FURTHER HUMAN PHYSIOLOGY

1 (a) *H. pylori* is implicated as a cause of stomach ulcers/cancer; antibodies show that the patient has been infected with *H. pylori*; (b) Any two of: incidence of stomach ulcers and cancer is higher in patients who had been infected with *H. pylori*; all patients with stomach cancer had been infected with *H. pylori*; some patients with stomach ulcers had not been infected so there must be alternative causes; correlation does not prove causation; (c)(i) higher incidence of duodenal inflammation in patients who had been infected; higher incidence of oesophagus inflammation in patients who had not been infected; (ii) *H. pylori* infects the stomach; toxins produced by *H. pylori* will pass on to the duodenum, not back to the oesophagus;

2 (a) SAN/pacemaker sends out a signal; signal spreads out through the walls of the atria (b) any two of: lub dup sounds made when valves close; closing valve causes vibration of blood in ventricle; rushing sounds due to flow of blood.

3 (a) $V_E$ increases as carbon dioxide concentration increases; greater increases in $V_E$ with successive increases in carbon dioxide concentration; (b) increases in carbon dioxide concentration in inspired air increase the blood concentration; detected by chemosensors in aorta/carotid artery; impulses sent to ventilation centre of brain/medulla; (c) further increases in $V_E$; until maximal $V_E$ is reached;

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*Andrew Allott* is a former chief examiner for IB Diploma Programme biology and is currently involved in examining and curriculum review. He has taught for over 25 years and is currently Head of Biology at Shrewsbury School, UK.

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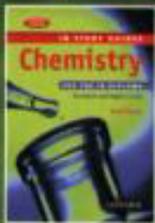
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