BIOZONE

QCE BIOLOGY UNITS 1&2

BIOZONE

QCE | BIOLOGY UNITS 1&2

BIOZONE Learning Media respectfully acknowledges the traditional custodians of the lands where we work and the places in which we live.

We pay our respects to ancestors and to all First Nations elders: past, present and emerging.

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Cover Photograph

Photo: Adobe Stock /Seregraff

The orange bearded dragon is a colour morph of the central (or inland) bearded dragon *(Pogona vitticeps)*. Beardeds dragons are a species of Australian lizard, related to iguanas. They occur in a range of arid to semiarid regions of Australia and are popular as pets.

Disclaimer

Although every care has been taken, Aboriginal and Torres Strait Islander people should be aware that this title may contain images of deceased persons.

The external weblinks (URLs) referenced in this book were correct at the time of publishing. However, due to the dynamic nature of the internet, some addresses may have changed, or cease to exist. While BIOZONE regrets any inconvenience that this may cause readers, no responsibility for any such changes or unforeseeable errors can be accepted by BIOZONE.

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QCE | BIOLOGY UNITS 1&2

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Contents

CODING: **Activity** is marked: ☐ to be done ☑ when completed Mandatory practicals in red SHE in orange

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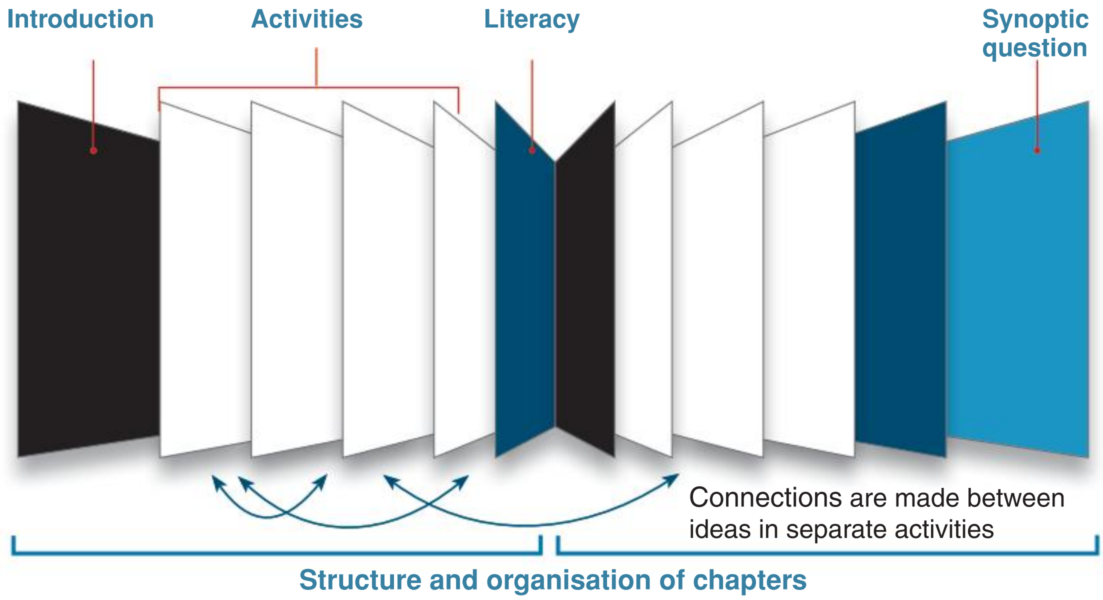
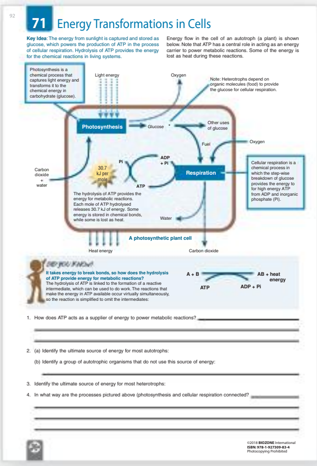
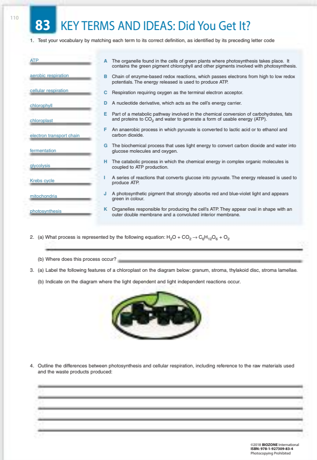
Using This Book

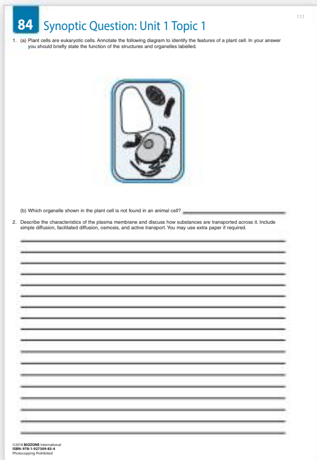
This first edition of Biology for QCE Units 1 & 2 has been specifically written to meet the content and skills requirements of the Queensland (QCE) Biology general senior syllabus. QCE Biology Units 1&2 focusses on foundational learning and features specific formative assessments, developing the skills and knowledge required for the summative assessments in Units 3 and 4. Each chapter introduction provides you with a concise guide to the knowledge and skills requirements for each unit of study. A wide range of activities will help you to build on what you already know, explore new topics, work collaboratively, and practise your skills in data handling and interpretation. We hope that you find the workbook valuable and that you make full use of its features.

- The outline of the chapter structure below will help you to navigate through the material in each chapter.









Introduction

- Provides a check list of unit objectives for the chapter.
- Identifies SHEs, mandatory and suggested practicals, and manipulative skills.
- Provides a useful list of important key terms.

Activities

- The KEY IDEA provides your focus for the activity.
- Annotated diagrams and photographs help you understand the content.
- Questions review the content of the page.

Literacy

- All chapters have a literacy activity based on the introductory key terms list and the chapter content.
- These activities test your understanding of biological terms and ideas in the chapter.

Synoptic question

- Synoptic questions conclude each unit and topic of study covered in the book.

- The chapter introduction provides you with a summary of the knowledge and skills requirements for the topic, phrased as a set of key skills and knowledge statements.

This identifies the unit and topic to which this chapter applies.

A list of key terms for the chapter allows you to construct your own glossary as you work through the activities.

Coloured flags identify points related to science as a human endeavour (*SHE*), manipulative skills (*SKILL*), and mandatory (red) and suggested (blue) practicals (*PRAC*)

Use the check boxes to identify and mark off the points as you complete them.

The activity in the book related to these statements.

UNIT 1
Topic 1

91

Energy and Metabolism

Activity number

Key terms
aerobic
alcoholic fermentation
anaerobic
ATP
autotrophic
Calvin cycle
carbohydrate
cellular respiration
chlorophyll
chloroplast
cristae
electron transport chain
ethanol
fermentation
glycolysis
grana
heterotrophic
Krebs cycle
lactic acid fermentation
light dependent reactions
light independent reactions
matrix
mitochondrion
photosynthesis
stroma
thylakoids

Obtaining energy for life

Key skills and knowledge

☐ 1 Explain the role of ATP (adenosine triphosphate) as an energy carrier in cells. Recall that organisms obtain the energy they need to recycle ATP from glucose molecules through the process of cellular respiration. Contrast the source of this glucose in autotrophs and heterotrophs. **71 77**

☐ 2 Compare cellular respiration and photosynthesis as energy transformation processes. Include reference to the relationship between the raw materials and products of the processes. Analyse diagrams and schematics of energy transfer. **71 79-81**

Photosynthesis

Key skills and knowledge

☐ 3 Describe the ecological role and importance of plants as producers. Recall that photosynthesis is an enzyme-controlled series of chemical reactions occurring in the chloroplasts of plant cells and it uses light energy to synthesis glucose. **72**

☐ 4 Summarise photosynthesis in both a word equation and a balanced chemical equation, identifying raw materials and end products. Identify the form in which the food is produced and what it is used for. Summarise photosynthesis in terms of the light dependent reactions and the light independent reactions (the Calvin cycle). **74**

☐ 5 Describe features of chloroplasts that are related to their role in photosynthesis. **73**

☐ 6 PRAC Investigate the effect of light on the outputs of photosynthesis. **75**

☐ 7 SHE Describe how enhancing photosynthesis could improve production of food and fuel, reduce dependence on fossil fuels, and improve sustainability. **76**

Cellular respiration

Key skills and knowledge

☑ 8 Explain why organisms need to respire, recalling the universal role of ATP in metabolism. Recognise that organisms can respire aerobically and anaerobically. **77**

☑ 9 Recognise that cellular respiration is an enzyme-controlled series of chemical reactions and that aerobic respiration requires oxygen. **79**

☑ 10 Recall the structure of a mitochondrion and its role in cellular respiration. Identify the main steps in the complete oxidation of glucose by aerobic cellular respiration: glycolysis, Krebs cycle, and electron transport chain. **79**

☑ 11 Summarise the reactions of aerobic respiration in a word equation and in a chemical equation, including the ATP yield. Teacher's note: The actual ATP yield is lower than the theoretical maximum yield of 36-38 ATP because of factors (such as membrane leakiness) that dissipate the proton gradient and reduce efficiency. **79**

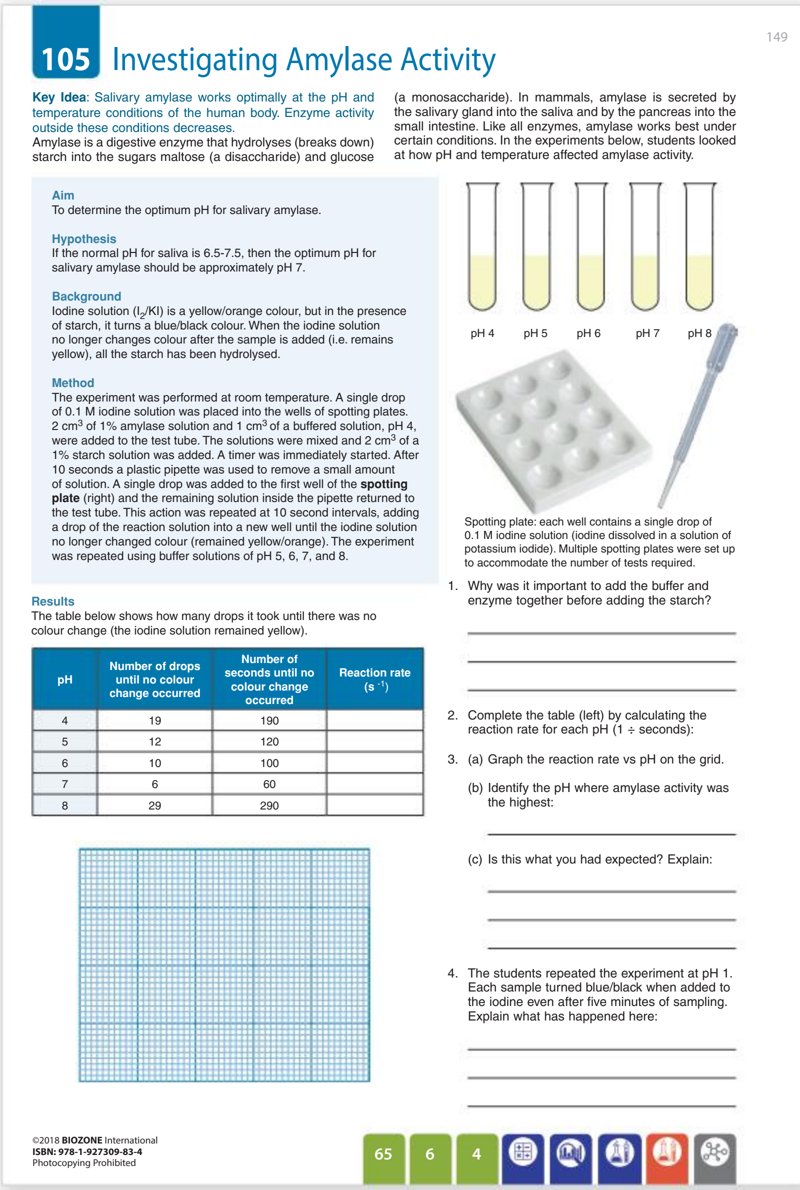
☐ 12 Describe anaerobic (without oxygen) pathways for ATP generation in eukaryotes: lactic acid fermentation in mammalian muscle and alcoholic fermentation in yeast and plant roots. Compare the energy yield from aerobic and anaerobic pathways. Teacher's note: Fermentation is not the same as anaerobic respiration, which, by definition, involves an electron transport chain with an electron acceptor other than oxygen, e.g. nitrate, sulfate, or elemental sulfur. ... phosphorylation and not an electrochemical gra... **81**

☐ 13 PRAC Measure oxygen consumption in respir... **78**

☐ 14 PRAC Measure the outputs of fermentation in y... **82**

Using the Tab System

- The tab system is a useful way to identify important parts of the QCE Biology syllabus. These may be suggested or mandatory (required). The tabs also allow you to see at a glance if online support is provided and if there are content links with other activities.



149

105 Investigating Amylase Activity

Key Idea: Salivary amylase works optimally at the pH and temperature conditions of the human body. Enzyme activity outside these conditions decreases.

Amylase is a digestive enzyme that hydrolyses (breaks down) starch into the sugars maltose (a disaccharide) and glucose (a monosaccharide). In mammals, amylase is secreted by the salivary gland into the saliva and by the pancreas into the small intestine. Like all enzymes, amylase works best under certain conditions. In the experiments below, students looked at how pH and temperature affected amylase activity.

Aim
To determine the optimum pH for salivary amylase.

Hypothesis
If the normal pH for saliva is 6.5-7.5, then the optimum pH for salivary amylase should be approximately pH 7.

Background
Iodine solution (I_2/KI) is a yellow/orange colour, but in the presence of starch, it turns a blue/black colour. When the iodine solution no longer changes colour after the sample is added (i.e. remains yellow), all the starch has been hydrolysed.

Method
The experiment was performed at room temperature. A single drop of 0.1 M iodine solution was placed into the wells of spotting plates. 2 cm^3 of 1% amylase solution and 1 cm^3 of a buffered solution, pH 4, were added to the test tube. The solutions were mixed and 2 cm^3 of a 1% starch solution was added. A timer was immediately started. After 10 seconds a plastic pipette was used to remove a small amount of solution. A single drop was added to the first well of the **spotting plate** (right) and the remaining solution inside the pipette returned to the test tube. This action was repeated at 10 second intervals, adding a drop of the reaction solution into a new well until the iodine solution no longer changed colour (remained yellow/orange). The experiment was repeated using buffer solutions of pH 5, 6, 7, and 8.

pH 4 pH 5 pH 6 pH 7 pH 8

Spotting plate: each well contains a single drop of 0.1 M iodine solution (iodine dissolved in a solution of potassium iodide). Multiple spotting plates were set up to accommodate the number of tests required.

Results
The table below shows how many drops it took until there was no colour change (the iodine solution remained yellow).

pH	Number of drops until no colour change occurred	Number of seconds until no colour change occurred	Reaction rate (s^{-1})
4	19	190	
5	12	120	
6	10	100	
7	6	60	
8	29	290	

1. Why was it important to add the buffer and enzyme together before adding the starch?
2. Complete the table (left) by calculating the reaction rate for each pH (1 ÷ seconds):
3. (a) Graph the reaction rate vs pH on the grid.
   (b) Identify the pH where amylase activity was the highest:
   (c) Is this what you had expected? Explain:
4. The students repeated the experiment at pH 1. Each sample turned blue/black when added to the iodine even after five minutes of sampling. Explain what has happened here:

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65 6 4

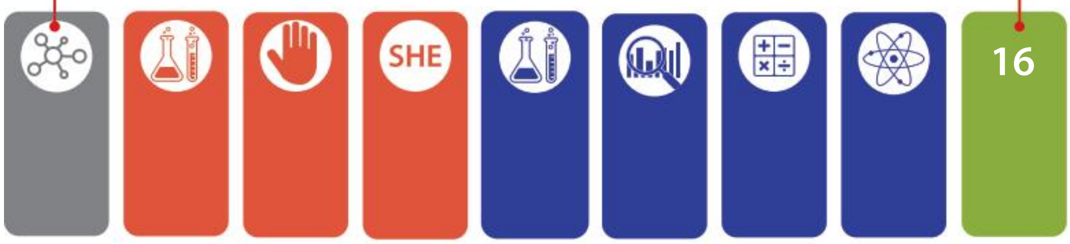
Page tabs show where science inquiry skills, practicals, or science as a human endeavour material has been incorporated into an activity. They also indicate if there is online support provided and suggest links to activities with related or background content.

Weblinks

This tab indicates the actiivty is supported with online content. Bookmark the weblinks page:
www.biozone.com.au/weblink/QCE1-9834
Access the external URL for the activity by clicking the link

Link

Connections are made between activities in different sections of the syllabus. These activities may contain related concepts or they may provide background information.



Red tabs indicate that the activity contains the following (L → R):

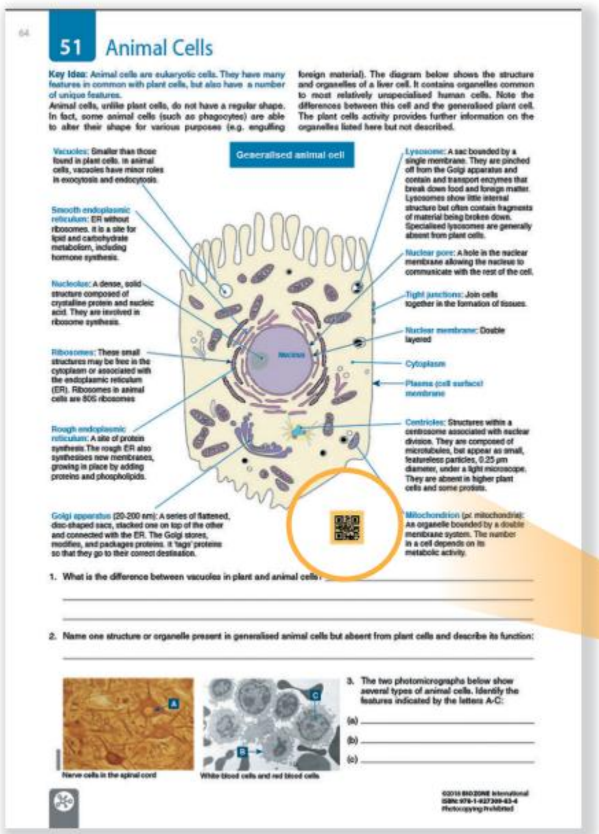
- Mandatory practical
- Manipulative skill
- Science as a human endeavour

Blue tabs indicate the activity contains the following (L → R):

- Suggested practical
- Data analysis and interpretation
- Tasks involving mathematical or numeracy skills
- Modelling

Using BIOZONE's Website

- BIOZONE's **Resource Hub** provides links to online content supporting the activities in the book. From this site (below), you can also explore BIOZONE's collection of annotated 3D models and check for any errata or clarifications to the book or model answers since printing. Activities with Resource Hub support are indicated by a **grey tab** (below) at the bottom of the activity page. Most activities have resources to support them.
- The external websites are generally narrowly focussed animations, illustrated content, or video clips relevant to some aspect of the activity on which they are cited. They provide great support to help your understanding.



Scan the **QR codes** on the activity pages. These link directly to informative and engaging 3D models. All models can be rotated and zoomed, and some contain informative annotations.

Answering Long Answer Questions

- Sometimes, you may be required to demonstrate your understanding by providing a written paragraph or essay.
- Open answer questions (meaning there is no definitive answer) are designed so that you can demonstrate your level of understanding. The question may give you some guidance as to what you should include in your answer, such as definitions of certain terms or to provide specific examples.
- In order to best answer the question, you need to lay out your answer in a clear and logical way so that the reader can easily see how you have demonstrated your understanding of the topic.
- The difference between answering a question well or poorly depends on how well you show your understanding.
  - Defining, drawing, annotating, or giving a description demonstrates a basic understanding of the material.
  - Explaining how a process works, why it works, and how changes to it may affect an outcome shows a deeper understanding of how the system works in that situation.
  - Linking biological ideas, comparing and contrasting, analysing, or justifying ideas shows both a deep understanding and an ability to translate that understanding to a new situation.
- The following example shows how an answer can be built up from a simple definition, through explanation, to comparisons and linking of ideas.

For the animal group mammals, discuss the relationship between the gas exchange system and the internal transport system. You should clearly show how they are linked and the role each plays in supporting a mammal's active lifestyle

How gas exchange is physically linked to transport system.

Description of the gas exchange system.

The gas exchange system in mammals is linked to the internal transport system at the gas exchange surface in the alveoli of the lungs. Inhaled air passes through the trachea to the bronchi, to the bronchioles and finally into the alveoli, microscopic sac-like structures at the terminal ends of bronchioles. Oxygen from the air diffuses through the gas exchange surface into the blood and binds to haemoglobin in the red blood cells. It is then transported to the body's cells. Haemoglobin greatly increases the amount of oxygen the blood can carry and supports a high oxygen demand (as in mammals).

Description of how oxygen is exchanged and carried through the transport system.

Carbon dioxide (CO_2) is picked up at the respiring tissues and is transported in the blood to the lungs where it diffuses into the alveoli and is exhaled. The diffusion of respiratory gases into and out of the blood proceeds because the diffusion gradients are maintained by the transport of gases to and from the gas exchange surface and continual exchange of air between the lungs and the external environment.

Explanation of how the diffusion of gases is maintained.

This system supports a mammal's active lifestyle (high metabolic rate) by continually supply oxygen to fuel metabolism and removing CO_2 (its waste product). The system can also adapt to increases in oxygen demand by increasing the volume of air breathed (more rapid breathing and deeper breaths) and increasing the speed at which the blood circulates (increasing heart rate to pump more blood per unit time).

Why the system supports the mammal's lifestyle.

How the system can adjust to changes in demand.

ALL UNITS
Skills

Basic Skills for QCE

Key terms

accuracy
bias
chi-squared test
control
controlled variable
dependent variable
estimate
experiment
graph
hypothesis
independent variable
mean
median
model (scientific)
observation
percentage
precision
prediction
proportion
qualitative data
quantitative data
rate
ratio
reliability (of data)
scientific method
significant figures
statistical test
table
trend
variable

Activity number

Inquiry is the basis of science

Key skills and knowledge [points also covered throughout QCE1&2]

Inquiry begins with observation

- ☐ 1 Describe the role of inquiry-based investigations in science. Show, through your work, your understanding of science as a non-linear process. **1**
- ☐ 2 Use a variety of methods to answer questions you raise as a result of observation. These include field and laboratory-based investigations, simulations and models, and data analysis. **4**
- ☐ 3 Use scientific models to illustrate biological processes and concepts, communicate information, make predictions, and describe systems. **2**

Communication

Key skills and knowledge [points also covered throughout QCE1&2]

The results of investigations must be communicated to peers to have value

- ☐ 4 Demonstrate an ability to communicate the findings of your investigations through oral and written presentations, including lab reports, and through graphs and/or contributions to online resources. **4 11**
- ☐ 5 Use a lab notebook or portfolio to organise your work and provide a record of ideas, methods, results, further questions, and references. **4 11**

Quantitative skills

Key skills and knowledge [points also covered throughout QCE1&2]

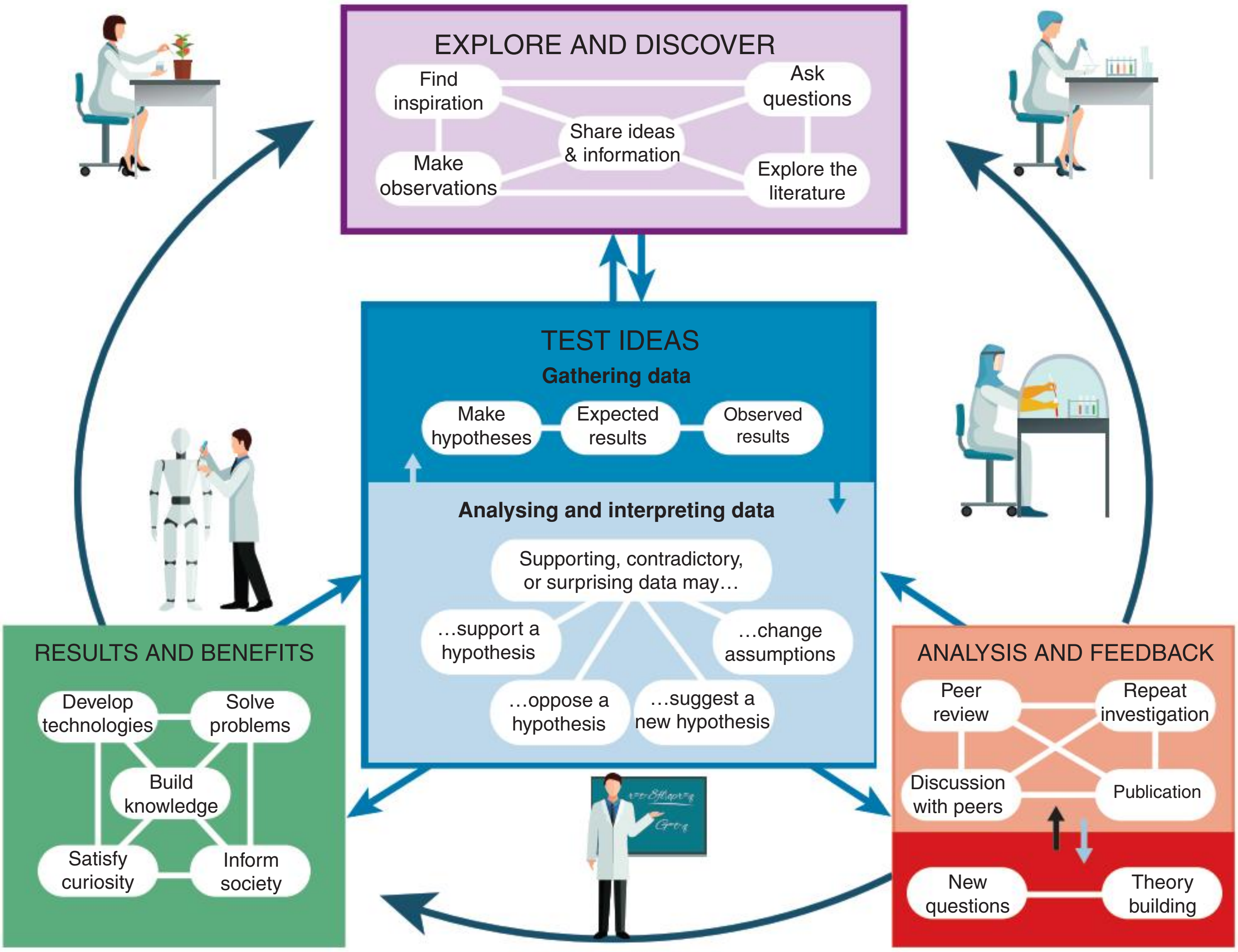
Quantitative reasoning is an essential part of inquiry in biology

- ☐ 6 Demonstrate ability to use basic mathematical skills to collect data. These include making counts and measurements. Distinguish between accuracy and precision (reliability) and understand their importance when collecting quantitative data. **3 4 5**
- ☐ 7 Demonstrate competence in use of ratios and proportions, scientific notation, and significant figures. Use estimation and calculation to analyse data. **6 7**
- ☐ 8 Demonstrate appropriate application of mathematical routines to data, e.g. calculating rates and percentages. Interpret and manipulate mathematical relationships in order to calculate and predict values. **6 7**
- ☐ 9 Use descriptive statistics (e.g. mean and standard deviation) and apply appropriate mathematical tools to analyse data and/or test hypotheses, e.g. linear regression, 95% confidence intervals, and some simple statistical tests such as Student's *t* and chi-squared. **14-21**
- ☐ 10 Use tables or spreadsheets to organise different types of data, including any calculated values (e.g. means and standard deviation). **14-16 19**
- ☐ 11 Construct graphs for different types of data, including logarithmic data and data collected during your investigations. Plot error in calculated values as appropriate (e.g. 95% confidence limits) and understand the value in doing this (in terms of confidence in the data). **11-13 16**

1 How Do We Do Science?

Key Idea: The scientific method is a rigorous process of observation, measurement, and analysis that helps us to explain phenomena and predict changes in a system.

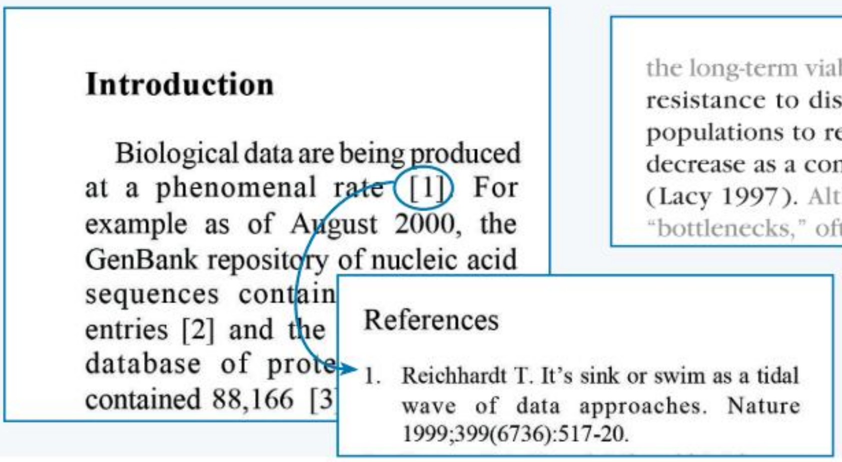
Scientific knowledge is gained through a non-linear, dynamic process called the **scientific method**. The scientific method is not a strict set of rules to be followed, but rather a way of approaching problems in a rigorous, but open-minded way. It involves inspiration and creativity, it is dynamic and context dependent, and usually involves collaboration. The model below is one interpretation of the scientific method.



Citation and references

All scientific work acknowledges sources of information through citation and a list of references. Citations support the statements made in the text in context, and all citations are then listed alphabetically, or identified and referenced sequentially by number. Internet sites are dated and site author acknowledged. Thorough and accurate citation and referencing shows you have explored the topic, have evidence to support your work, and you are not taking credit for work that is not your own. Each publication sets its own particular referencing style and these can vary widely. In your own work, it is most important to be consistent.

Citation and reference by numbers

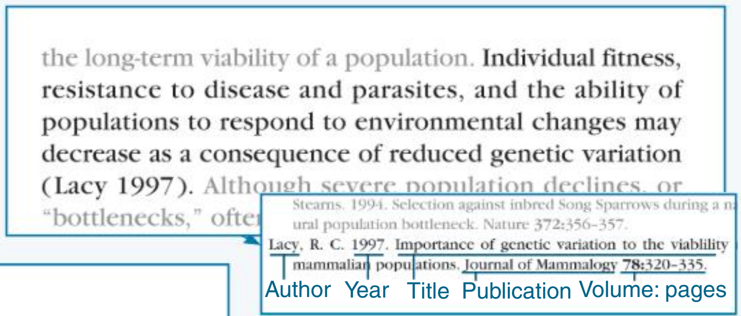

Introduction

Biological data are being produced at a phenomenal rate [1]. For example as of August 2000, the GenBank repository of nucleic acid sequences contain… entries [2] and the database of prote… contained 88,166 [3…

References

1. Reichhardt T. It's sink or swim as a tidal wave of data approaches. Nature 1999;399(6736):517-20.

Citation and reference by authors


the long-term viability of a population. Individual fitness, resistance to disease and parasites, and the ability of populations to respond to environmental changes may decrease as a consequence of reduced genetic variation (Lacy 1997). Although severe population declines, or "bottlenecks," ofte…

Stearns. 1994. Selection against inbred Song Sparrows during a n… ural population bottleneck. Nature 372:356–357.

Lacy, R. C. 1997. Importance of genetic variation to the viability of mammalian populations. Journal of Mammalogy 78:320–335.

The style you choose is not as important as being consistent, thorough, and honest about drawing on other people's work. All the information needed to locate the reference should be included (above).

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Observations, questions, and hypotheses

- Observation is the beginning of any scientific investigation. Often the best investigations are based on a series of fortuitous or specific observations. For example, in 1765, Edward Jenner developed the first vaccination for smallpox after hearing that milkmaids who contracted cowpox (a harmless disease) never got smallpox. After observing a phenomenon, questions must be asked: What causes the phenomenon? Is it linked to other observations? Can it be manipulated?
- An observation may generate a number of plausible hypotheses. Scientific hypotheses are tentative testable explanations for observed phenomena. A hypothesis leads to one or more predictions about the way a system will behave so a research hypothesis is usually written to include a testable prediction, i.e if X is true, then the effect of Y will be Z.
- For every hypothesis, there is a corresponding null hypothesis, i.e. a hypothesis of no difference or no effect. A null hypothesis allows a hypothesis to be tested statistically and can be rejected if the experimental results are statistically significant. Hypotheses are not static, but may be modified as more information becomes available.

Example: Two observations were made, as described below and used to produce a hypothesis:

Observation 1: Some caterpillar species are brightly coloured and appear to be conspicuous to predators (e.g. insectivorous birds). Predators appear to avoid these species. These caterpillars are often found in groups, rather than being solitary.

Observation 2: Some caterpillar species are cryptic in their appearance or behaviour. Their camouflage is so convincing that, when alerted to danger, they are difficult to see against their background. Such caterpillars are usually found alone.

Hypothesis: If bright colors indicate to predators that caterpillars are distasteful, birds will not eat them. The corresponding **null hypothesis** would be there is no difference in palatability between the bright and cryptically coloured caterpillars.

Assumptions

Any biological investigation requires you to make **assumptions** about the biological system you are working with. Assumptions are features of the system (and your investigation) that you assume to be true but do not (or cannot) test. Possible assumptions about the biological system above are described in the box right:

- Insectivorous birds have colour vision.
- Caterpillars that look bright or cryptic to us, also appear that way to insectivorous birds.
- Insectivorous birds learn about the palatability of prey by tasting them.

1. What is the role of citation and correct referencing when reporting on scientific investigations? ____________________

2. Study the diagram opposite and write a paragraph on the scientific process and the role of surprising results in science. Attach it to this page. At the end of your course, reexamine what you wrote. Have your ideas changed?

3. Based on the hypothesis above, generate a prediction about the behaviour of insectivorous birds towards caterpillars:

4. During a routine preparation of bacterial colonies on agar plates, a laboratory assistant noticed that the colonies left overnight on the side of a bench near a heating unit grew faster than those left on the opposite side of the bench. The assistant decided to test this observation by experiment:

   (a) State a hypothesis for the investigation: ____________________

   (b) Generate a prediction based on the hypothesis: ____________________

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2 Systems and System Models

Key Idea: Systems are assemblages of interrelated components working together. Models can be mathematical or visual representations of these systems.

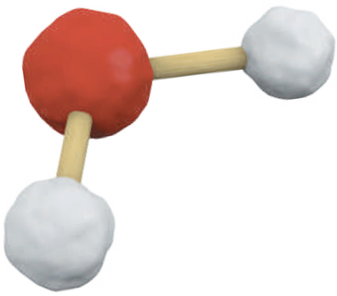
A system is a set of interrelated components that work together. Energy flow in ecosystems (such as the Queensland rainforest on the right), gene regulation, interactions between organ systems, and feedback mechanisms are all examples of systems studied in biology. Modelling systems helps to understand how they work. A **model** is a representation of a system and is useful for breaking a complex system down into smaller parts that can be studied more easily. Often only part of a system is modeled. As scientists gather more information about a system, more data can be put into the model so that eventually it represents the real system more closely.

Modelling systems

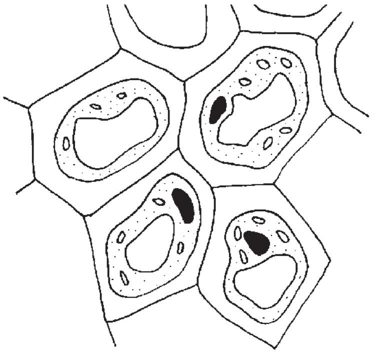
There are many different ways to model systems or their components. Often seeing data presented in different ways can help us to understand it better. Some common examples of models are shown here.

Visual models

Visual models can include drawings, such as these plant cells (below right) or three dimensional physical or computer generated models. Three dimensional models can be made out of materials such as modelling clay and ice-cream sticks, like the model of a water molecule (below left).

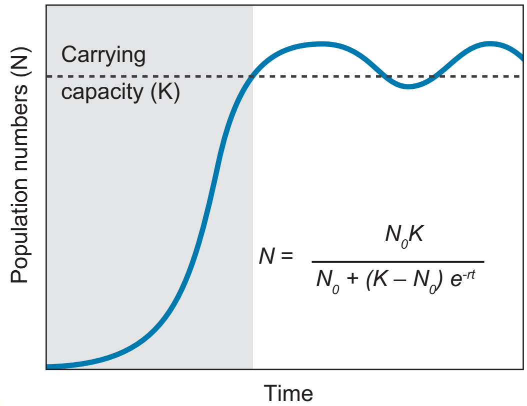


James Hedberg



Mathematical models

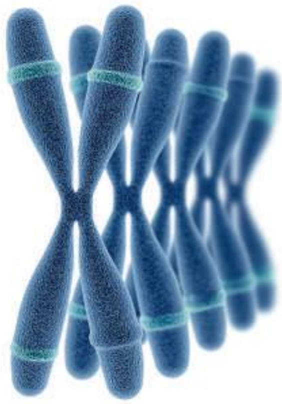
Displaying data in a graph or as a mathematical equation, as shown below for logistic growth, often helps us to see relationships between different parts of a system.



$$N = \frac{N_0 K}{N_0 + (K - N_0)\, e^{-rt}}$$

Analogy

An analogy is a comparison between two things. Comparing a biological system to an everyday object can sometimes help us to understand it better. For example, the heart pumps blood in blood vessels in much the same way a fire truck pumps water from a fire hydrant through a hose. Similarly, the DNA in chromosomes is like a library. Extending that analogy further, the steps in baking a cake from a recipe book provide an analogy for how the instructions in DNA (the recipe) are translated into a specific protein (the cake).



The DNA in chromosomes is like ...... a library of books

1. What is a system? ______________________________

____

2. (a) What is a model? ______________________________

____

(b) Why do scientists often study one part of a system rather than the whole system? ______________________________

____

____

____

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3 Types of Data

Key Idea: Data is information collected during an investigation. Data may be quantitative, qualitative, or ranked.

When planning a biological investigation, it is important to consider the type of data that will be collected. It is best to collect quantitative or numerical data, , because it is mathematically versatile and easier to analyse it objectively (without bias).

Types of data

Quantitative

Characteristics for which measurements or counts can be made, e.g. height, weight, number.

Discontinuous

e.g. Number of children in a family (3, 0, 4)

Continuous

e.g. Height of children in a family (1.5 m, 0.8 m)

Qualitative

Non-numerical and descriptive, e.g. sex, colour, presence or absence of a feature, viability (dead/alive).

e.g. Sex of children in a family (male, female)

Ranked

Data which can be ranked on a scale that represents an order, e.g. abundance (abundant, common, rare); colour (dark, medium, pale).

e.g. Birth order in a family (1, 2, 3)

Discontinuous or discrete data:

The unit of measurement cannot be split up (e.g. can't have half a child).

Continuous data:

The unit of measurement can be a part number (e.g. 5.25 kg).

A: Skin colour

B: Eggs per nest

C: Tree trunk diameter

D: Rate of growth in seedlings

1. For each of the photographic examples A-C above, classify the data as quantitative, ranked, or qualitative:

   (a) Skin colour: ______________________________

   (b) Number of eggs per nest: ______________________________

   (c) Tree trunk diameter: ______________________________

   (d) Rate of seedling growth: ______________________________

2. Why is it best to collect quantitative data where possible in biological studies? ______________________________

   ____

   ____

   ____

3. Give an example of data that could not be collected quantitatively and explain your answer: ______________________________

   ____

   ____

   ____

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4 Planning a Practical Investigation

Key Idea: Practical work carried out in a careful and methodical way makes analysis of the results much easier.

A major part of any practical investigation is collecting the data. Practical work may be laboratory or field based. Typical laboratory based experiments involve investigating how a biological response is affected by manipulating a particular **variable**, e.g. temperature. The data collected for a quantitative practical task should be recorded systematically, with due attention to safe practical techniques, a suitable quantitative method, and accurate measurements to an appropriate degree of precision. If your quantitative practical task is carried out well, and you have taken care throughout, your evaluation of the experimental results will be much more straightforward and less problematic.

Carrying out your practical work

Preparation

Familiarise yourself with the equipment and its set up. Calibrate equipment if necessary to give accurate measurements.

Read through the methods and identify key stages and how long they will take.

Execution and recording

Know how you will take your measurements and how often. Record your results systematically as you go in a log book. You could record results a hand-written table or in a spreadsheet. If using a data logger, data will be logged.

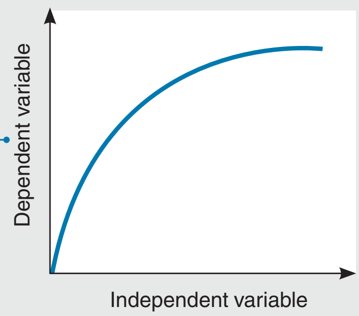
Analysis and reporting

Analyse the data. Tables can summarise data. Graphs present the data to show patterns and trends. Statistical tests can determine the significance of results. Present your findings, e.g. as a poster, a digital presentation, or an oral report.

Identifying variables

A **variable** is any characteristic or property able to take any one of a range of values. Investigations often look at the effect of changing one variable on another. It is important to identify all variables in an investigation: independent, dependent, and controlled, although there may be nuisance factors of which you are unaware. In all fair tests, only one variable is changed by the investigator.

Dependent variable
- Measured during the investigation.
- Recorded on the y axis of the graph.



Controlled variables
- Factors that are kept the same or controlled.
- List these in the method, as appropriate to your own investigation.

Independent variable
- Set by the experimenter.
- Recorded on the graph's x axis.

Experimental controls

A **control** refers to a standard or reference treatment or group in an experiment. It is the same as the experimental (test) group, except that it lacks the one variable being manipulated by the experimenter. Controls are used to demonstrate that the response in the test group is due a specific variable (e.g. temperature). The control undergoes the same preparation, experimental conditions, observations, measurements, and analysis as the test group. This helps to ensure that responses observed in the treatment groups can be reliably interpreted.

- The experiment above tests the effect of a certain nutrient on microbial growth. All the agar plates are prepared in the same way, but the control plate does not have the test nutrient applied.
- Each plate is inoculated from the same stock solution, incubated under the same conditions, and examined at the same set periods. The control plate sets the baseline; any growth above that seen on the control plate is attributed to the nutrient.

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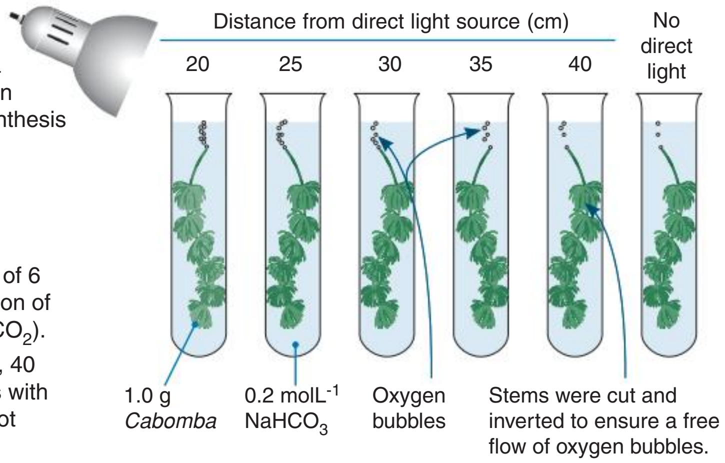
Investigation: Effect of light on rate of photosynthesis

Background

The aquarium plant, *Cabomba aquatica*, will produce a stream of oxygen bubbles when illuminated. The oxygen bubbles are a waste product of the process of photosynthesis (overall equation below right), which produces glucose ($C_6H_{12}O_6$) for the plant. The rate of oxygen production provides an approximation of photosynthetic rate.

The method

- 6 x 1.0 g of *Cabomba* stems were placed into each of 6 test-tubes filled with 10 mL room temperature solution of 0.2 mol L^{-1} sodium hydrogen carbonate (to supply CO_2).
- Test tubes were placed at distances (20, 25, 30, 35, 40 cm) from a 60W light source (light intensity reduces with distance at a predictable rate). One test tube was not exposed to the light source.
- Before recording, the *Cabomba* stems were left to acclimatise to the new light level for 5 minutes. The bubbles emerging from the stem were counted for a period of three minutes at each distance.



$$6CO_2 + 12H_2O \xrightarrow{\text{Light}} C_6H_{12}O_6 + 6O_2 + 6H_2O$$

1. Write a suitable aim for this experiment: ______________________________

2. Write a possible hypothesis for this experiment: ______________________________

3. (a) What is the independent variable in this experiment? ______________________________

   (b) What is the range of values for the independent variable? ______________________________

   (c) Name the unit for the independent variable: ______________________________

   (d) How could you better quantify the independent variable? ______________________________

4. (a) What is the dependent variable in this experiment? ______________________________

   (b) Name the unit for the dependent variable: ______________________________

   (c) What equipment might have made it easier to record the response of the dependent variable accurately? Predict when it would have been most needed:

   ____

   (d) What is the sample size for each treatment?______________________________

   (e) What could you change in the design of the experiment to guard against unexpected or erroneous results?

   ____

5. Which tube is the control for this experiment? ______________________________

6. Identify two assumptions being made about this system:

   (a) ______________________________

   (b) ______________________________

7. Identify one variable that might have been controlled in this experiment, and how it could have been monitored:

   ____

8. How might you test the gas being produced is oxygen: ______________________________

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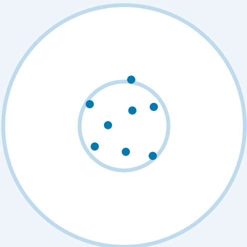
5 Accuracy and Precision

Key Idea: Accuracy refers to the correctness of a measurement (how true it is to the real value). Precision refers to how close the measurements are to each other.

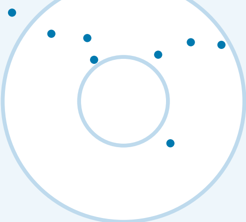
Accuracy refers to how close a measured or derived value is to its true value. Simply put, it is the correctness of the measurement. Precision refers to how close repeated measurements are to each other, i.e. the ability to be exact. A balance with a fault in it could give very precise (repeatable) but inaccurate (untrue) results. Data can only be reported as accurately as the measurement of the apparatus allows and is often expressed as significant figures (the digits in a number which express meaning to a degree of accuracy.

Accurate but imprecise



The measurements are all close to the true value but quite spread apart.
Analogy: The arrows are all close to the bullseye.

Inaccurate and imprecise

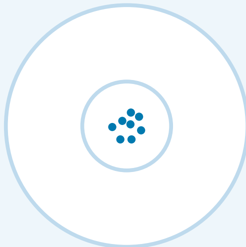


The measurements are all far apart and not close to the true value.
Analogy: The arrows are spread around the target.

Precise but inaccurate

The measurements are all clustered close together but not close to the true value.
Analogy: The arrows are all clustered close together but not near the bullseye.

Accurate and precise



The measurements are all close to the true value and also clustered close together.
Analogy: The arrows are clustered close together near the bullseye.

Increasing precision

The accuracy of a measurement refers to how close the measured value is to the true value. The precision of a measurement relates to its repeatability. In most laboratory work, we usually assume a piece of equipment (e.g. a pipette) performs accurately, so making precise measures is the most important consideration. We can test precision by taking repeated measurements from individual samples. Precision and reliability are synonymous and describe how dependably an observation is the same when repeated.

Increasing accuracy

Population studies present us with an additional problem. When a researcher makes measurements of some variable (e.g. fish length), they are usually trying to obtain an estimate of the true value for a parameter of interest (e.g. the mean size of fish). Populations are variable, so we can more accurately estimate a population parameter if we take a large number of random samples from the population.

A digital device such as the pH meter (above left) will deliver precise measurements, but its accuracy will depend on correct calibration.

The precision of measurements taken with instruments such as callipers (above) will depend on the skill of the operator. Precise measurements provide reliable data.

1. Distinguish between accuracy and precision: ______________________________

2. Describe why it is important to take measurements that are both accurate and precise: ______________________________

3. A researcher is trying to determine the temperature at which an enzyme becomes denatured. Their temperature probe is incorrectly calibrated. Discuss how this might affect the accuracy and precision of the data collected:

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Accuracy and equipment

The accuracy of a measurement can be increased by increasing the number of measurements taken. For example, the accuracy of the mean mass of individuals in a population can be increased by increasing the number of individuals measured (i.e. increasing the sample size).

In many cases, the accuracy of the measuring equipment needs to be taken into account. For example, electronic balances may give readings to one or more decimal places based on their accuracy (laboratory balances may read to a hundred thousandths of a gram).

The table below illustrates the difference between a balance weighing to 0.1 of a gram and 0.01 of a gram

Sample	1	2	3	4	5	Mean
Mass (g) (2 s.f)	1.1	1.2	1.4	1.2	1.3	1.2
Mass (g) (3 s.f)	1.12	1.23	1.44	1.19	1.28	1.25

The difference in mean mass is slight (just 0.05 g) but over larger samples or larger masses the differences can add up.

The table above also shows the importance of significant figures (s.f.). The actual numerical mean for the second row is 1.252. However because we are measuring to three significant figures we cannot be sure of the final number thus the answer must be given in the same significant figures as the measurements.

Reducing error

Sometimes reducing error requires taking more measurements over a longer period of time. For example, hypothetical waves breaking on a shore do so with a relatively regular frequency. Recording the time between one wave breaking and the next depends when the wave is defined as breaking. This may be difficult to determine precisely for each individual wave and the waves may be breaking too quickly to allow enough time to elapse for recordings to be made accurately (especially if the timer is being started and stopped by a person).

To increase the accuracy of measuring the period between each wave, it is best to record the time for a number of waves to break (e.g. 10) and divide by that number to obtain the period between each wave. This has the effect of allowing for slight variations in the period and reduces the total error in the measurement.

Example: Actual wave period: 5.0 seconds.
Accuracy of timer (i.e. reaction speed) 0.3 seconds

Measurements of individual periods (seconds): 5.4, 5.7, 5.7, 5.8, 4.5, 4.6, 5.7, 5.8, 5.1, 5.3, Mean: 5.4

In each measurement above, the error is about 0.3 seconds producing an error of up to 6.7% (0.3 ÷ 4.5 x 100) of the recorded value of a wave period.

If the time recorded for ten waves to break was 51.1 seconds, then the time for one wave to break is 5.1 seconds. The error is spread over the whole 51.1 seconds (0.3 ÷ 51.1) and thus is much smaller at just 0.6% of the wave period.

4. The period of a pendulum is based on the length of the pendulum and the mass at its end. Two students measure the time it takes for a pendulum to swing back and forth (its period). Student A measures three individual swings and calculates a mean value. Student B measures three sets of ten swings and calculates a mean. Each student measures the accuracy of the timer as 0.2 seconds. The results are shown below:

Student A	
	Time for swing (s)
1	2.7
2	2.1
3	2.5
Mean (1 swing)	

Student B	
Set	Time for ten swings (s)
1	20.3
2	20.1
3	19.8
Mean (10 swings)	
1 swing	

(a) Calculate the mean for each student's results and the time for one swing for student B.

(b) Explain why student B's results are more accurate than student A's: ______

5. In a class of 20 students, the individual heights of the students in cm are: 135, 139, 141, 146, 147, 149, 156, 151, 158, 155, 156, 159, 161, 167, 162, 163, 161, 172, 171, 170.

(a) Calculate the mean height of the students: ______

(b) A person takes a sample of five of the students: 139, 151, 162, 172, 170. Calculate the mean of the sample and comment on its accuracy:

(c) A second person takes a sample of ten of the students: 135, 146, 147, 156, 155, 156, 161, 167, 162, 170. Calculate the mean of the sample and comment on its accuracy:

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6 Working with Numbers

Key Idea: Using correct mathematical notation and being able to carry out simple calculations and conversions are fundamental skills in biology.

Mathematics is used in biology to analyse, interpret, and compare data. It is important that you are familiar with mathematical notation (the language of mathematics) and can confidently apply some basic mathematical principles and calculations to your data.

Decimal and standard form

Decimal form (also called ordinary form) is the longhand way of writing a number (e.g. 15,000,000). Very large or very small numbers can take up too much space if written in decimal form and are often expressed in a condensed **standard form**. For example, 15,000,000 is written as 1.5×10^7 in standard form. In standard form a number is always written as $A \times 10^n$, where A is a number between 1 and 10, and n (the exponent) indicates how many places to move the decimal point. n can be positive or negative.

For the example above, A = 1.5 and n = 7 because the decimal point moved seven places (see below).

$$1\,5\,0\,0\,0\,0\,0\,0 = 1.5 \times 10^7$$

Small numbers can also be written in standard form. The exponent (n) will be negative. For example, 0.00101 is written as 1.01×10^{-3}.

$$0.\,0\,0\,1\,0\,1 = 1.01 \times 10^{-3}$$

Converting can make calculations easier. Work through the following example to solve $4.5 \times 10^4 + 6.45 \times 10^5$.

1. Convert $4.5 \times 10^4 + 6.45 \times 10^5$ to decimal form:

   ____

2. Add the two numbers together: _______________

3. Convert to standard form: _______________

Rates

Rates are expressed as a measure per unit of time and show how a variable changes over time. Rates are used to provide meaningful comparisons of data that may have been recorded over different time periods.

Often rates are expressed as a mean rate over the duration of the measurement period, but it is also useful to calculate the rate at various times to understand how rate changes over time. The table below shows the reaction rates for a gas produced during a chemical reaction. A worked example for the rate at 4 minutes is provided below the table.

Time (Minute)	Cumulative gas produced (cm^3)	Rate of reaction ($cm^3\ min^{-1}$)
0	0	0
2	34	17
4	42	4*
6	48	3
8	50	1
10	50	0

* Gas produced between 2 - 4 min: $42\ cm^3 - 34\ cm^3 = 8\ cm^3$

Rate of reaction between 2 - 4 min: $8 \div 2\ min = 4\ cm^3\ min^{-1}$

Conversion factors and expressing units

Measurements can be converted from one set of units to another by the use of a **conversion factor**.

A conversion factor is a numerical factor that multiplies or divides one unit to convert it into another. Conversion factors are commonly used to convert non-SI units to SI units (e.g. converting pounds to kilograms). Note that mL and cm^3 are equivalent, as are L and dm^3.

In the space below, convert 5.6 cm^3 to mm^3 (1 cm^3 = 1000 mm^3):

4. ___________________________________

The value of a variable must be written with its units where possible. SI units or their derivations should be used in recording measurements: volume in cm^3, dm^3, or litre (L), mass in kilograms (kg) or grams (g), length in metre (m), time in seconds (s).

For example the rate of oxygen consumption would be expressed:

Oxygen consumption ($cm^3 g^{-1} s^{-1}$)

Estimates

When carrying out mathematical calculations, typing the wrong number into your calculator can put your answer out by several orders of magnitude. An **estimate** is a way of roughly calculating what answer you should get, and helps you decide if your final calculation is correct.

Numbers are often rounded to help make estimation easier. The rounding rule is, if the next digit is 5 or more, round up. If the next digit is 4 or less, it stays as it is.

For example, to estimate 6.8 x 704 you would round the numbers to 7 x 700 = 4900. The actual answer is 4787, so the estimate tells us the answer (4787) is probably right.

Use the following examples to practice estimating:

5. 43.2 x 1044: ___________________________________

6. 3.4 x 72 ÷ 15: ___________________________________

   ____

7. 658 ÷ 22: ___________________________________

Probability

Probability is how likely something is to happen. It is an important part of biology. Its uses include calculating the statistical significance of a difference between means or the probability of an event occurring.

The probability of an event ranges from 0 to 1. The sum of all probabilities equals 1.

Product rule: for independent events A and B the probability (P) of A and B occurring is P(A) x P(B). For example, the probability two children born one after the other both being male is 0.5 x 0.5 = 0.25.

Sum rule: For mutually exclusive events Y and Z the probability that one will occur (Y or Z) is P(Y) + P(Z). E.g. in an Aa x Aa cross the probability a person will have a dominant phenotype = 0.25 + 0.5 = 0.75.

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7 Fractions, Percentages, and Ratios

Key Idea: Percentages and ratios are alternative ways to express fractions. All forms are commonly used in biology.

The data collected in the field or laboratory are called raw data. Data are often expressed in ways that make them easy to understand, visualise, and work with. Fractions, ratios, and percentages are widely used in biology and are often used to provide a meaningful comparison of sample data where the sample sizes are different.

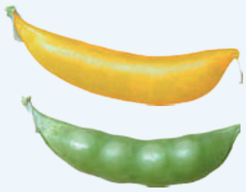
Fractions

- Fractions express how many parts of a whole are present
- Fractions are expressed as two numbers separated by a solidus (/) (e.g. 1/2)
- The top number is the numerator. The bottom number is the denominator. The denominator can not be zero.
- Fractions are often written in their simplest form (the top and bottom numbers cannot be any smaller, while still being whole numbers). Simplifying makes working with fractions easier.

In a class of 20 students, five had blue eyes. This fraction is 5/20. To simplify this fraction, divide the numerator and denominator by a common factor (a number which both are divisible by). In this instance the lowest common factor is five (1/4). To add fractions with different denominators, obtain a common denominator, add numerators, then simplify.

Ratios

- Ratios give the relative amount of two or more quantities, and provide an easy way to identify patterns.
- Ratios do not require units.
- Ratios are expressed as **a : b**.
- Ratios are calculated by dividing all the values by the smallest number.



Pea pod shape:
Ratio = 2.95 : 1

Pea seed shape and color:
Ratio = 9 : 2.8 : 2.9 : 1

Example: Calculating phenotype ratios in Mendelian genetics

Percentages

- Percentages are expressed as a fraction of 100 (e.g. 20/100 = 20%).
- Percentages provide a clear expression of what proportion of data fall into any particular category, e.g. for pie graphs.
- Allows meaningful comparison between different samples.
- Useful to monitor change (e.g. % increase from one year to the next).

Volume of food coloring (cm^3)	Volume of water (cm^3)	Concentration of solution (%)
10	0	100
8	2	80
6	4	60
4	6	40
2	8	20
0	10	0

Example: Producing standards for a calibration curve.

1. (a) A student prepared a slide of the cells of an onion root tip and counted the cells at various stages in the cell cycle. The results are presented in the table (right). Calculate the ratio of cells in each stage (show your working):

   (b) Assuming the same ratio applies in all the slides examined in the class, calculate the number of cells in each phase for a cell total count of 4800.

Cell cycle stage	No. of cells counted	No. of cells calculated
Interphase	140	
Prophase	70	
Telophase	15	
Metaphase	10	
Anaphase	5	
Total	240	4800

2. Simplify the following fractions:

   (a) 3/9: ______ (b) 84/90: ______ (c) 11/121: ______

3. In the fraction example pictured above 5/20 students had blue eyes. In another class, 5/12 students had blue eyes. What fraction of students had blue eyes in both classes combined?

4. The total body mass and lean body mass for women with different body types is presented in the table (right). Complete the table by calculating the % lean body mass column.

Women	Body mass (kg)	Lean body mass (kg)	% lean body mass
Athlete	50	38	
Lean	56	41	
Normal weight	65	46	
Overweight	80	48	
Obese	95	52	

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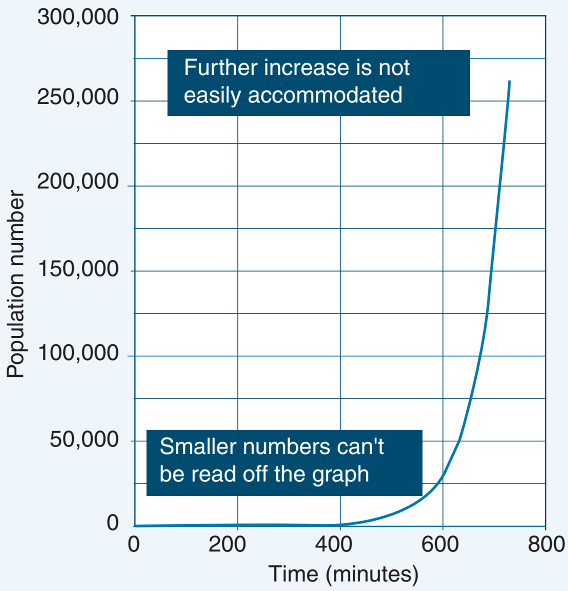
8 Dealing with Large Numbers

Key Idea: Exponential functions are common in biology and may involve very large numbers. Exponential changes in numbers are defined by a function, which is simply a rule that allows us to calculate an output for any given input.

In biology, numerical data indicating scale can often decrease or increase exponentially. Examples include the exponential growth of populations, exponential decay of radioisotopes, and the pH scale. Exponential changes are defined by a function that allows us to calculate an output for any input. The numbers associated with exponential growth can be very large and are often log transformed. Log transformations of exponential numbers can make them easier to handle.

Exponential function

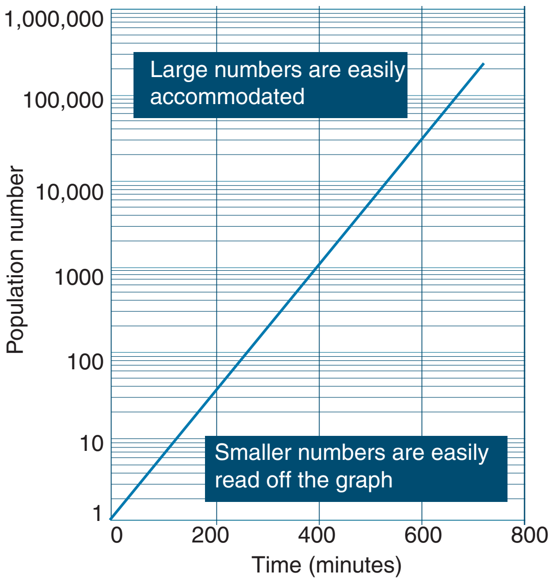
- Exponential growth occurs at an increasingly rapid rate in proportion to the growing total number or size.
- In an exponential function, the base number is fixed (constant) and the exponent is variable.
- The equation for an exponential function is $y = c^x$.
- Exponential growth and decay (reduction) are possible.
- Exponential changes in numbers are easy to identify because the curve has a J-shape appearance due to its increasing steepness over time.
- An example of exponential growth is the growth of a microbial population in an unlimiting, optimal growth environment.



Example: Cell growth in a yeast culture where growth is not limited by lack of nutrients or build up of toxins.

Log transformations

- A log transformation makes very large numbers easier to work with. The log of a number is the exponent to which a fixed value (the base) is raised to get that number. So $\log_{10}(1000) = 3$ because $10^3 = 1000$.
- Both $\log_{10}$ (common logs) and $\log_e$ (natural logs or *ln*) are commonly used.
- Log transformations are useful for data where there is an exponential increase or decrease in numbers. In this case, the transformation will produce a straight line plot.
- To find the log10 of a number, e.g. 32, using a calculator, key in log 32 = . The answer should be 1.51.
- Alternatively, the untransformed data can be plotted directly on a log-linear scale (as below). This is not difficult. You just need to remember that the log axis runs in exponential cycles. The paper makes the log for you.



Example: The same yeast cell growth plotted on a log-linear scale. The y axis present 6 exponential cycles

1. Why is it useful to plot exponential growth using semi-log paper? ______

______

______

2. What would you do to show yeast exponential growth (left plot above) as a straight line plot on normal graph paper?

______

3. Log transformations are often used when a value of interest ranges over several orders of magnitude. Can you think of other examples of data from the natural world where the data collected might show this behavior?

______

______

______

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9 Practising with Data

Key Idea: This activity allows you to practise working with data and applying the skills you have learned in previous activities.

1. Complete the transformations for each of the tables below. The first value is provided in each case.

(a) Photosynthetic rate at different light intensities

Light intensity (%)	Average time for leaf disc to float (min)	Reciprocal of time* (min^{-1})
100	15	0.067
50	25	
25	50	
11	93	
6	187	

** Reciprocal of time gives a crude measure of rate.*

(b) Plant water loss using a bubble potometer

Time (min)	Pipette arm reading (cm^3)	Plant water loss (cm^3 min^{-1})
0	9.0	–
5	8.0	0.2
10	7.2	
15	6.2	
20	4.9	

(c) Incidence of cyanogenic clover in different areas

Clover plant type	Frost free area		Frost prone area		Totals
	Number	%	Number	%	
Cyanogenic	124	78	26		
Acyanogenic	35		115		
Total	159				

(d) Frequency of size classes in a sample of eels

Size class (mm)	Frequency	Relative frequency (%)
0-50	7	2.6
50-99	23	
100-149	59	
150-199	98	
200-249	50	
250-299	30	
300-349	3	
Total	270	

2. Convert the following decimal form numbers to standard form:

(a) 8970 ________________ (b) 0.046 ________________ (c) 1,467,851 ________________

3. Convert the following standard form numbers to decimal form:

(a) 4.3×10^{-1} ________________ (b) 0.0031×10^{-2} ________________ (c) 6.2×10^{4} ________________

4. (a) The table on the right shows the nutritional label found on a can of chilli beans. Use the information provided to complete the table by calculating the percentage composition for each of the nutritional groups listed:

(b) How much of the total carbohydrates is made up of:

Dietary fibre? ________________

Sugars? ________________

(c) Manufacturers do not have to state the volume of water, which makes up the remainder of the serving size. What percentage of the can of beans is water?

____

Chilli beans nutrition facts Serving size 1 cup (253 g)		
Amount per serving		**% composition**
Total fat	**8 g**	
– Saturated fat	**3 g**	
Total carbohydrate	**22 g**	
– Dietary fibre	**9 g**	
– Sugars	**4 g**	
Protein	**25 g**	

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10 Apparatus and Measurement

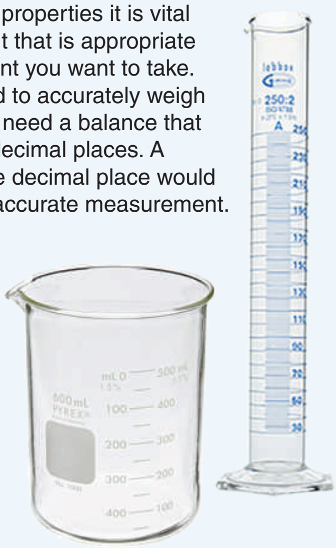
Key Idea: The apparatus used in experimental work must be appropriate for the experiment or analysis and it must be used correctly to eliminate experimental errors.

Using scientific equipment can generate experimental errors. These can be reduced by selecting the right equipment for what you want to measure and by using it correctly. Some error is inevitable, but evaluating experimental error helps to interpret and assess the validity of the results.

Selecting the correct equipment

When measuring physical properties it is vital that you choose equipment that is appropriate for the type of measurement you want to take. For example, if you wanted to accurately weigh out 5.65 g of sucrose, you need a balance that accurately weighs to two decimal places. A balance that weighs to one decimal place would not allow you to make an accurate measurement.

Study the glassware (right). Which would you use if you wanted to measure 225 mL? The graduated cylinder has graduations every 10 mL whereas the beaker has graduations every 50 mL. It would be more accurate to measure 225 mL in a graduated cylinder.



Percentage errors

Percentage error is a way of mathematically expressing how far out your result is from the ideal result. The equation for measuring percentage error is:

$$\frac{\text{experimental value - ideal value}}{\text{ideal value}} \times 100$$

For example, to determine the accuracy of a 5 mL pipette, dispense 5 mL of water from the pipette and weigh the dispensed volume on a balance.
The mass (g) = volume (mL). The volume is 4.98 mL.

$$\frac{\text{experimental value } (\mathbf{4.98}) \text{ - ideal value } (\mathbf{5.0})}{\text{ideal value } (\mathbf{5.0})} \times 100$$

The percentage error = –0.4% (the negative sign tells you the pipette is dispensing **less** than it should).

Recognising potential sources of error

It is important to know how to use equipment correctly to reduce errors. A spectrophotometer measures the amount of light absorbed by a solution at a certain wavelength. This information can be used to determine the concentration of the absorbing molecule (e.g. density of bacteria in a culture). The more concentrated the solution, the more light is absorbed. Incorrect use of the spectrophotometer can alter the results. Common mistakes include incorrect calibration, errors in sample preparation, and errors in sample measurement.

A cuvette (left) is a small clear tube designed to hold spectrophotometer samples. Inaccurate readings occur when:

- The cuvette is dirty or scratched (light is absorbed giving a falsely high reading).
- Some cuvettes have a frosted side to aid alignment. If the cuvette is aligned incorrectly, the frosted side absorbs light, giving a false reading.
- Not enough sample is in the cuvette and the beam passes over, rather than through the sample, giving a lower absorbance reading.

1. Assume that you have the following measuring devices available: 50 mL beaker, 50 mL graduated cylinder, 25 mL graduated cylinder, 10 mL pipette, 10 mL beaker. What would you use to accurately measure:

   (a) 21 mL: ______________ (b) 48 mL: ______________ (c) 9 mL: ______________

2. Calculate the percentage error for the following situations (show your working):

   (a) A 1 mL pipette delivers a measured volume of 0.98 mL: ______________

   (b) A 10 mL pipette delivers a measured volume of 9.98 mL: ______________

   (c) The pipettes used in (a) and (b) above both under-delivered 0.02 mL, yet the percentage errors are quite different. Use this data to describe the effect of volume on percentage error:

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11 Drawing Graphs

Key Idea: Graphs are useful for visually displaying numerical data, trends, and relationships between variables.

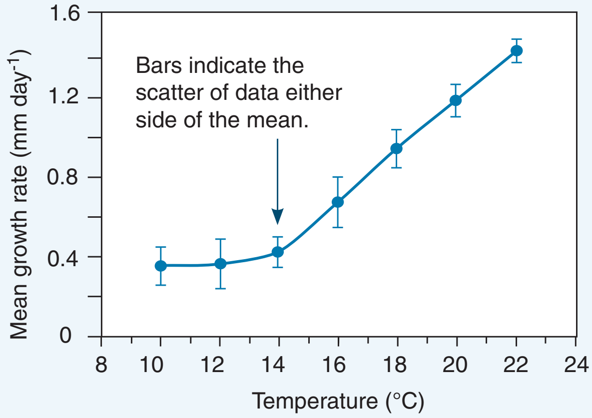
Graphs are an excellent way to summarise trends in data or relationships between different variables. Presenting graphs properly requires attention to a few basic details, including correct orientation and labelling of the axes, and accurate plotting of points. Before representing data graphically, it is important to identify the kind of data you have. Common graphs include scatter plots and line graphs (for continuous data), and bar charts (for categorical data). For continuous data with calculated means, points can be connected. On scatter plots, a line of best fit is often drawn.

Guidelines for line graphs

WHEN TO USE: Use a line graph when both variables are continuous and one variable (the independent variable) affects another, the dependent variable. Important features include:

- The data must be continuous for both variables. The independent variable is often time or experimental treatment. The dependent variable is generally the biological response.
- The relationship between two variables can be represented as a continuum and the data points are plotted accurately and connected directly (point to point).
- Line graphs may be drawn with measure of error (right). The data are presented as points (which are calculated means), with error bars above and below, indicating the variability in the data (e.g. standard deviation).

Growth rate in peas at different temperatures

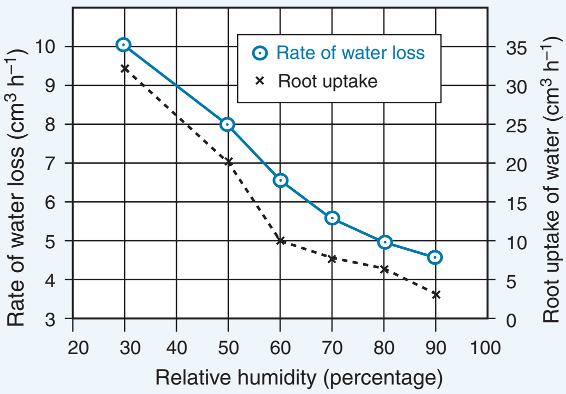


Plotting multiple data sets

A single figure (graph) can be used to show two or more data sets, i.e. more than one curve can be plotted per set of axes. This type of presentation is useful when comparing the trends for two or more treatments, or the response of one species against the response of another. Important points regarding this format are:

- If the two data sets use the same measurement units and a similar range of values for the dependent variable, one scale on the y axis is used.
- If the two data sets use different units and/or have a very different range of values for the dependent variable, two scales for the y axis are used (see right). The scales can be adjusted if necessary to avoid overlapping plots
- The two curves are distinguished with a key.

Water loss and root uptake rates in peas at different relative humidity

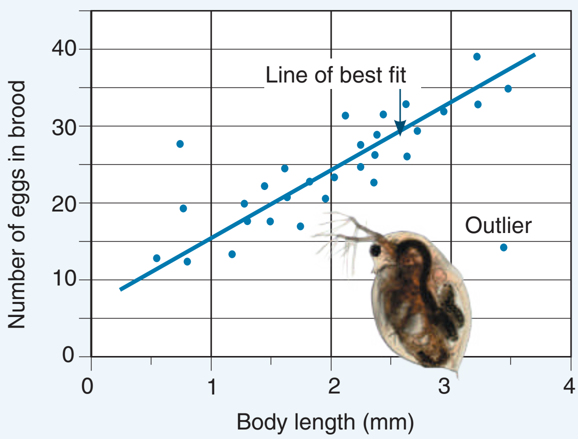


Guidelines for scatter graphs

WHEN TO USE: Use a scatter graph to display continuous data where there are two interdependent variables.

- The data must be continuous for both variables.
- There is no independent variable, but the variables are often correlated, i.e. they vary together in a predictable way.
- Useful to determine the relationship between two variables.
- The points on the graph are not connected, but a line of best fit is often drawn through the points to show the relationship between the variables (this may be computer generated with a value assigned to the goodness of the fit).
- Obvious outliers (points that lie well outside most of the scatter) are usually disregarded from analyses.

Body length vs brood size in *Daphnia*



> **Interpolation**: For both line and scatter graphs, the fitted line can be used to find an unknown value inside the set of data points. This is called interpolation.

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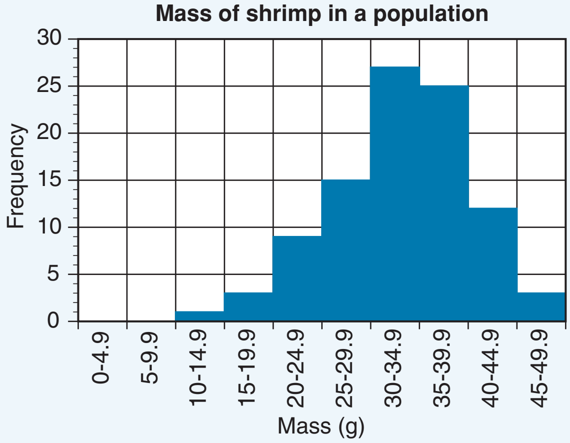
Guidelines for histograms

WHEN TO USE: Use a histogram when one variable is continuous and the other is a frequency (counts). These plots produce a frequency distribution, because the y-axis shows the number of times a measurement or value was obtained. Important features of histograms include:

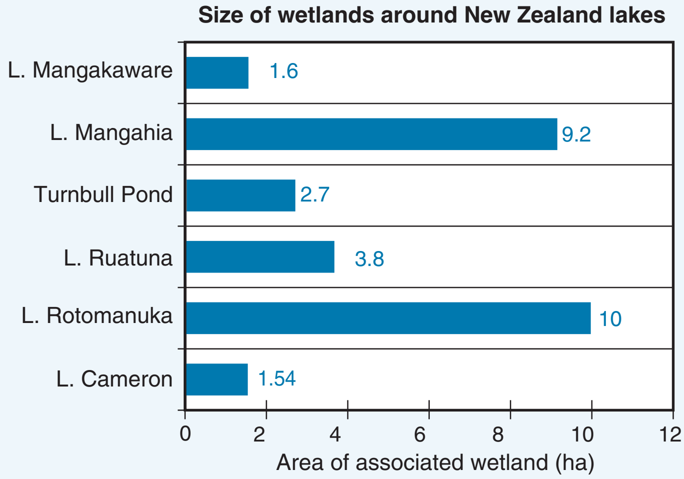
- The data are numerical and continuous (e.g. height or weight) so the bars touch.
- The x-axis usually records the class interval. The y-axis usually records the number of individuals in each class interval.



Guidelines for bar and column graphs

WHEN TO USE: Use a bar or column graph for data that are non-numerical and discrete (categorical) for one variable. There are no dependent or independent variables. Important features include:

- Data for one variable are discontinuous, non-numerical categories (e.g. place, color, species), so the bars do not touch.
- Data values may be entered by the bars if you wish.
- Multiple sets of data can be displayed side by side to compare (e.g. males and females in the same age group).
- Axes may be reversed so that the categories are on the x axis, i.e. the bars can be vertical or horizontal. When they are vertical, these graphs are called column graphs.



1. Determine what type of graph is appropriate for each of the following examples:

   (a) Arm span vs height in humans: ______

   (b) Daily energy requirement for different species of deer: ______

   (c) Number of fish of each size in a population: ______

   (d) Mean volume of water used per person per day in different North American cites: ______

   (e) Mean catalase reaction rate at different temperatures: ______

   (f) Number of eggs per brood in different breeds of chickens: ______

   (g) Mean monthly rainfall vs mean monthly temperature: ______

2. For the plots on the previous page:

   (a) Use interpolation to determine the mean growth rate of pea seedlings at 17°C: ______

   (b) Use interpolation to determine the number of eggs per brood in a 1.5 mm long *Daphnia*: ______

   (c) Use interpolation to determine the rate of water loss in peas at 40% relative humidity: ______

3. Extrapolation, i.e. predicting a data value that lies outside the range of available data, is not recommended practice.

   (a) Suggest why you should not extrapolate to find data values? ______

   ______

   (b) Can you think of an example to illustrate your decision? ______

   ______

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12 Interpreting Line Graphs

Key Idea: The equation for a straight line is y = mx + c. A line may have a positive, negative, or zero slope.

The equation for a linear (straight) line on a graph is y = mx + c. The equation can be used to calculate the gradient (slope) of a straight line and tells us about the relationship between x and y (how fast y is changing relative to x). For a straight line, the rate of change of y relative to x is always constant. A line may have a positive, negative, or zero slope.

Measuring gradients and intercepts

The equation for a straight line is written as:

y = mx + c

Where:

y = the y-axis value

m = the slope (or gradient)

x = the x-axis value

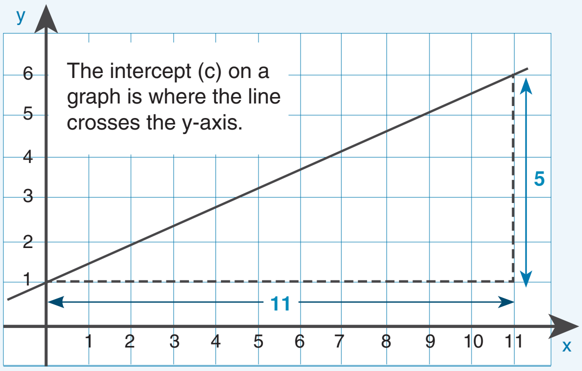
c = the y intercept (where the line cross the y-axis).

Determining "m" and "c"

To find "c" just find where the line crosses the y-axis.
To find m:

1. Choose any two points on the line.
2. Draw a right-angled triangle between the two points on the line.
3. Use the scale on each axis to find the triangle's vertical length and horizontal length.
4. Calculate the gradient of the line using the equation:

$$\frac{\text{change in y}}{\text{change in x}}$$

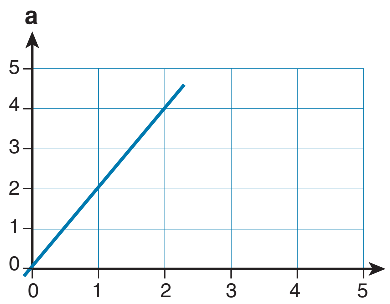


For the example above:
c = 1
m = 0.45 (5 ÷11)

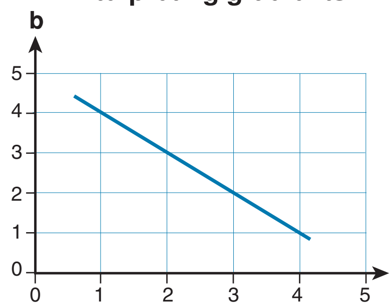
Once c and m have been determined you can choose any value for x and find the corresponding value for y.

For example, when x = 9, the equation would be:
y = 9 x 0.45 + 1
y = 5.05

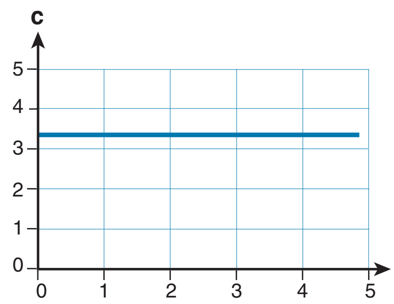
Interpreting gradients



Positive gradients: the line slopes upward to the right (y is increasing as x increases).



Negative gradients: the line slopes downward to the right (y is decreasing as x increases).



Zero gradients: the line is horizontal (y does not change as x increases).

1. State the gradient for graphs a, b, and c (above): (a)____________ (b) ____________ (c) ____________

2. For a straight line y = 3x + 2,

   (a) Identify the value of c: ____________ (b) Determine y if x = 4: ____________

3. For the graph (right):

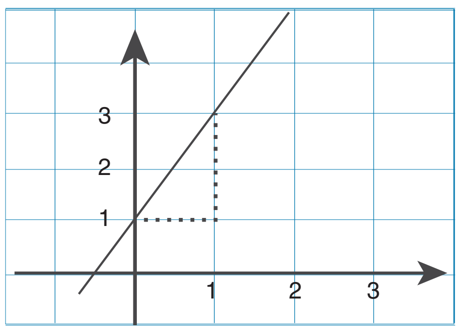
   (a) Identify the value of c: ____________

   (b) Calculate the value of m: ____________

   (c) Determine y if x = 2: ____________

   ____

   (d) Describe the slope of the line: ____________



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13 Correlation or Causation

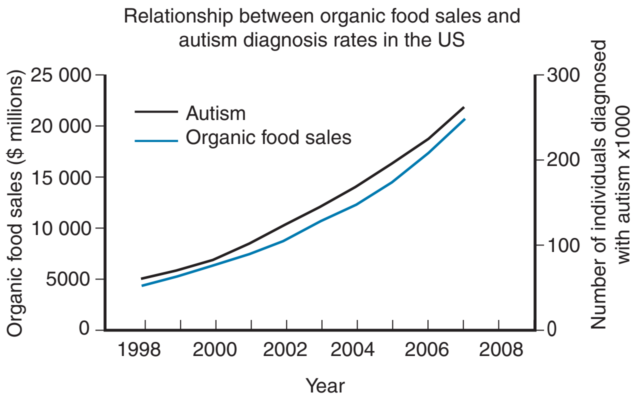
Key Idea: A correlation is a mutual relationship or association between two or more variables. A correlation between two variables does not imply that one causes change in the other.

Researchers often want to know if two variables have any **correlation** (relationship) to each other. This can be achieved by plotting the data as a scatter graph and drawing a line of best fit through the data, or by testing for correlation using a statistical test. The strength of a correlation is indicated by the correlation coefficient (r), which varies between 1 and -1. A value of 1 indicates a perfect (1:1) relationship between the variables. A value of -1 indicates a 1:1 negative relationship and 0 indicates no relationship between the variables.

Correlation does not imply causation

You may come across the phrase "correlation does not necessarily imply causation". This means that even when there is a strong correlation between variables (they vary together in a predictable way), you cannot assume that change in one variable caused change in the other.

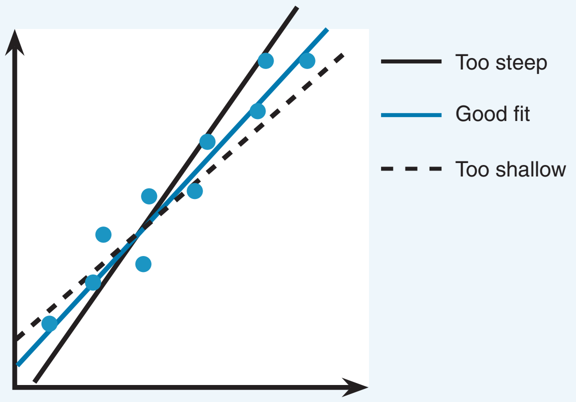
Example: When data from the organic food association and the office of special education programmes is plotted (below), there is a strong correlation between the increase in organic food and rates of diagnosed autism. However it is unlikely that eating organic food causes autism, so we can not assume a causative effect here.



Drawing the line of best fit

Some simple guidelines need to be followed when drawing a line of best fit on your scatter plot.

- Your line should follow the trend of the data points.
- Roughly half of your data points should be above the line of best fit, and half below.
- The line of best fit does not necessarily pass through any particular point.
- The line of best fit should pivot around the point which represents the mean of the x and the mean of the y variables.



1. What does the phrase "correlation does not imply causation" mean? ____________________

____

____

2. A student measured the hand span and foot length measurements of 21 adults and plotted the data as a scatter graph (right).

(a) Draw a line of best fit through the data:

(b) Describe the results: ____________________

____

____

____

____

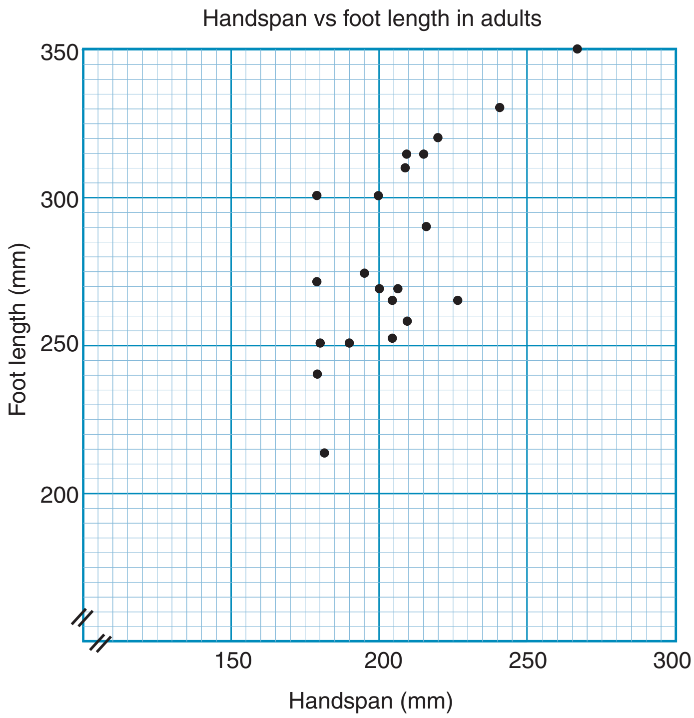
(c) Using your line of best fit as a guide, comment on the correlation between handspan and foot length:

____

____

____

____



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14 Mean, Median, and Mode

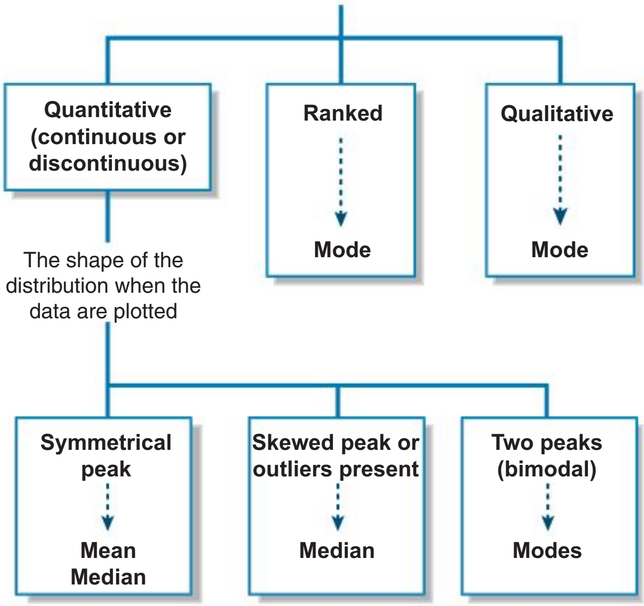
Key Idea: Mean, median, and mode are measures of the central tendency of data. The distribution of the data will determine which measurement of central tendency you use.

Measures of a biological response are usually made from more than one sampling unit. In lab-based investigations, the sample size (the number of sampling units) may be as small as three or four (e.g. three test-tubes in each of four treatments). In field studies, each individual may be a sampling unit, and the sample size can be very large (e.g. 100 individuals). It is useful to summarise data using descriptive statistics. **Descriptive statistics**, such as mean, median, and mode, can identify the central tendency of a data set. Each of these statistics is appropriate to certain types of data or distribution (as indicated by a frequency distribution).

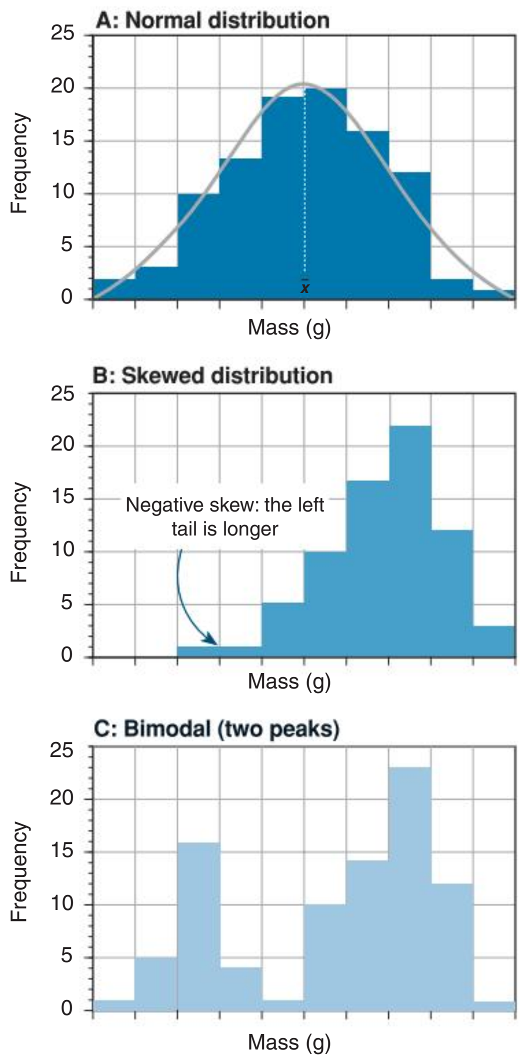
Variation in data

Whether they are obtained from observation or experiments, most biological data show variability. In a set of data values, it is useful to know the value about which most of the data are grouped, i.e. the centre value. This value can be the mean, median, or mode depending on the type of variable involved (see below). The main purpose of these statistics is to summarise important features of your data and to provide the basis for statistical analyses.

Type of variable sampled



The shape of the distribution will determine which statistic (mean, median, or mode) best describes the central tendency of the sample data.



Statistic	Definition and use	Method of calculation
Mean	• The average of all data entries. • Measure of central tendency for normally distributed data.	• Add up all the data entries. • Divide by the total number of data entries.
Median	• The middle value when data entries are placed in rank order. • A good measure of central tendency for skewed distributions.	• Arrange the data in increasing rank order. • Identify the middle value. • For an even number of entries, find the mid point of the two middle values.
Mode	• The most common data value. • Suitable for bimodal distributions and qualitative data.	• Identify the category with the highest number of data entries using a tally chart or a bar graph.
Range	• The difference between the smallest and largest data values. • Provides a crude indication of data spread.	• Identify the smallest and largest values and find the difference between them.

When NOT to calculate a mean:

In some situations, calculation of a simple arithmetic mean is not appropriate.

Remember:

- *DO NOT* calculate a mean from values that are already means (averages) themselves.
- *DO NOT* calculate a mean of ratios (e.g. percentages) for several groups of different sizes. Go back to the raw values and recalculate.
- *DO NOT* calculate a mean when the measurement scale is not linear, e.g. pH units are not measured on a linear scale.

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1. The birth weights of 60 newborn babies are provided right. Create a tally chart (frequency table) of the weights in the table provided below. Choose an appropriate grouping of weights.

Weight (kg)	Tally	Total

Birth weights (kg)

NEED HELP? See Activity 11

3.740	3.380	4.510	3.135	3.260
3.830	2.660	3.800	3.090	3.430
3.530	3.375	4.170	3.830	3.510
3.095	3.840	4.400	3.970	3.230
3.630	3.630	3.770	3.840	3.570
1.560	3.810	3.400	4.710	3.620
3.910	2.640	3.825	4.050	3.260
4.180	3.955	3.130	4.560	3.315
3.570	2.980	3.400	3.350	3.230
2.660	3.350	3.260	3.380	3.790
3.150	3.780	4.100	3.690	2.620
3.400	3.260	3.220	1.495	3.030

2. (a) On the graph paper (right) draw a frequency histogram for the birth weight data.

(b) What type of distribution does the data have?

____

____

____

(c) Predict whether mean, median, or mode would be the best measure of central tendency for the data:

____

(d) Explain your reason for your answer in (c):

____

____

____

(e) Calculate the mean, median, and mode for the birth weight data:

Mean: _______________

Median: _______________

Mode: _______________

(f) What do you notice about the results in (e)? _______________

____

____

(g) Explain the reason for this: _______________

____

____

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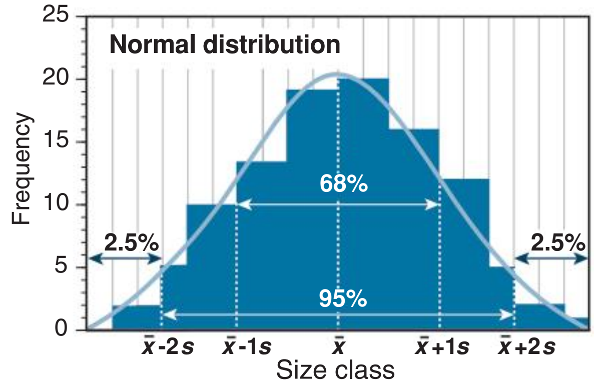
15 What is Standard Deviation?

Key Idea: Standard deviation is used to quantify the variability around the central value and evaluate the reliability of estimates of the true mean.

While it is important to know the central tendency (e.g. mean) of a data set, it is also important to know how well this value represents the data set as a whole. For a normal distribution, this can be evaluated using the standard deviation, which is a simple value that quantifies the spread in the data. If the standard deviation is small, more of the values will be clustered about the mean value.

Standard deviation

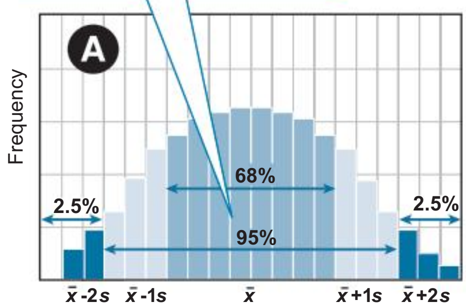
- Standard deviation is usually presented as $\bar{x} \pm s$. In normally distributed data, 68% of all data values will lie within one standard deviation (s) of the mean ($\bar{x}$) and 95% of all values will lie within two standard deviations of the mean (right).
- Different sets of data can have the same mean and range, yet a different data distribution. In both the data sets below, 68% of the values lie within the range $\bar{x} \pm 1s$ and 95% of the values lie within $\bar{x} \pm 2s$. However, in B, the data values are more tightly clustered around the mean.
- Standard deviation is easily calculated using an spreadsheet. Data should be entered as columns. In a free cell, type the formula for standard deviation and select the cells containing the data values, enclosing them in parentheses.



Histogram A has a larger standard deviation; the values are spread widely around the mean.

Both plots show a normal distribution with a symmetrical spread of values about the mean.

Histogram B has a smaller standard deviation; the values are clustered more tightly around the mean.

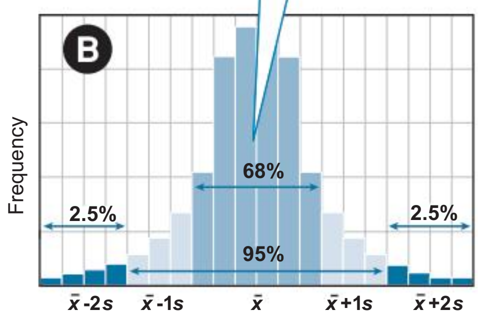


Calculating *s*

$$s = \sqrt{\frac{\sum(x - \bar{x})^2}{n - 1}}$$

$\sum(x - \bar{x})^2$ = sum of squared deviations from the mean

n = sample size. n -1 provides a unbiased s for small sample sizes (large samples can use n).



1. Two sample data sets of rat body length have the same mean. The first data set has a much larger standard deviation than the second data set. What does this tell you about the spread of data around the mean in each case? Which data set is likely to provide the most reliable estimate of body length in the rat population being sampled and why?

____

____

____

2. The data on the right shows the heights for 29 male swimmers.

   (a) Calculate the mean for the data: ____________________

   (b) Use manual calculation, a calculator, or a spreadsheet to calculate the standard deviation (s) for the data:

   ____

   (c) State the mean ± 1s: ____________________

   (d) What percentage of values are within 1s of the mean? ____________________

   (e) What does this tell you about the spread of the data? ____________________

   ____

   ____

Raw data: Height (cm)

178	177	188	176	186	175
180	181	178	178	176	175
180	185	185	175	189	174
178	186	176	185	177	176
176	188	180	186	177	

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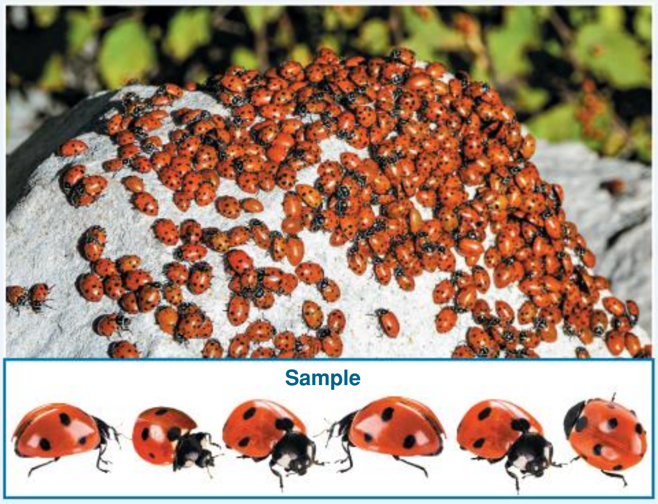
16 Reliability of the Mean

Key Idea: 95% confidence limits help to evaluate the reliability of the sample mean as an estimate of the population mean.

You have already seen how to use the standard deviation (s) to quantify the spread or dispersion in your data. Usually, you will also want to know how good your sample mean ($\bar{x}$) is as an estimate of the true population mean (μ). You can do this by calculating the 95% confidence interval (95% CI). The mean ± the 95% CI gives the **95% confidence limits**. On average, 95 times out of 100, the true population mean will lie within the confidence limits.

Reliability of the sample mean

- When we take measurements from samples of a larger population, we are using those samples as indicators of the trends in the whole population. Therefore, when we calculate a sample mean (the statistic), it is useful to know how close that value is to the true population mean (μ) for that attribute (the parameter).
- If you can determine the reliability of the sample mean, it will enable you to make inferences about the aspect of the population in which you are interested. Statistics based on samples and used to estimate population parameters are called **inferential statistics**.
- **Example**: If we calculated the mean number of spots from a sample of six ladybird beetles, how reliable is this statistic as an indicator of the mean number of spots in the whole population? We can find out by calculating the **95% confidence interval**.



Step 1: Calculate standard error (SE)

The standard error (SE) is simple to calculate and is usually a small value. Standard error is given by the standard deviation divided by the square root of n, where n is the sample size.

$$SE = \frac{s}{\sqrt{n}}$$

Step 2: Use SE to calculate the 95% confidence interval

SE is required to calculate the 95% confidence interval (CI) of the mean. This is simple: just multiply SE by the value of t at P = 0.05 (from a *t* table) for the appropriate degrees of freedom (df) for your sample (n – 1). Part of the t table is provided for you below.

$$95\%\ CI = SE \times t_{P(n-1)}$$

Critical values of Student's *t* at P = 0.05

Use this table to calculate 95% confidence interval

df	*P* 0.05
1	12.71
2	4.303
3	3.182
4	2.776
5	2.571
6	2.447
7	2.365
8	2.306
9	2.262
10	2.228
20	2.086
30	2.042
40	2.021
60	2.000
120	1.980
>120	1.960

Value of *t* at n – 1 = 5

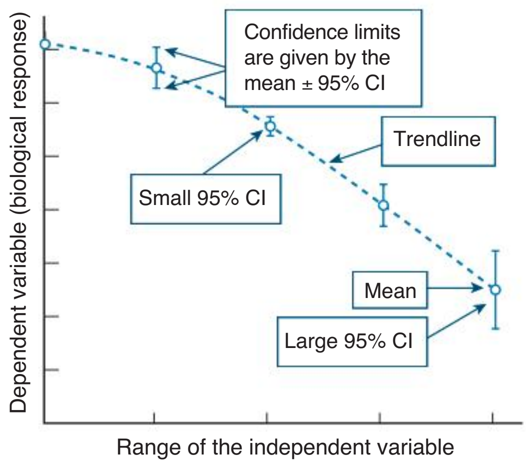
As the sample becomes very large, the value of *t* becomes smaller. For very large samples, *t* is fixed at 1.96, so the 95% CI is slightly less than twice the SE.

Maximum value of *t* at this level of *P*

Step 3: Plotting your confidence intervals

Once you have calculated the 95% CI for the means in your data, you can plot them as error bars on your graph. Note that the 95% confidence limits are given by the value of the mean ± 95%CI. A 95% confidence limit (i.e. P = 0.05) tells you that, on average, 95 times out of 100, the limits will contain the true population mean. Note that each of the plotted points represents a mean of 10 values.

Relationship of Y against X
(± 95%confidence intervals, n = 10)



All these statistics, including a plot of the data with Y error bars, can be calculated using a programme such as Microsoft Excel®.

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Clover root weevil

- The clover root weevil (*Sitona lepidus*) is a pest of white clover pastures. The adults feed on clover leaves, while the larvae feed on clover nodules and roots, causing root loss and a reduction in nitrogen fixation.
- Research has indicated that different pastures have different susceptibility to infestation by clover root weevil (left). Armed with this knowledge, two students reasoned that the most susceptible grass type would have the greatest weevil population. The students chose five pasture types, and recorded the number of weevil larvae in each pasture type at six sample sites (sample area 1 m^2). Their results are presented in the table below.

		Environment				
	Sample	Perennial ryegrass	Fescue	White clover	Red clover	Chicory
Number of weevils	1	42	42	48	42	45
	2	45	46	54	46	44
	3	41	38	48	45	45
	4	42	41	52	42	38
	5	49	45	49	44	40
	6	43	44	52	44	47

1. Complete the table below by calculating the mean, standard deviation, standard error, and 95% confidence interval (95% CI) for each of the grass environments.

	Perennial ryegrass	Fescue	White clover	Red clover	Chicory
Mean					
Standard deviation					
Standard error					
95% CI					

2. Select the appropriate graph format and plot the means for each of the grass environments below. Include bars to show the 95% confidence intervals.

3. Study your plot and decide if there are any significant differences between the abundance of clover root weevils in the five environments. Use your analysis to write a conclusion for the investigation below:

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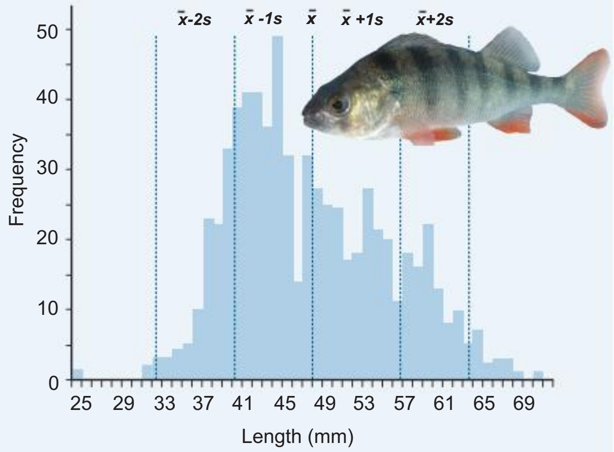
17 Detecting Bias in Samples

Key Idea: Sampling method can affect the results of a study, especially if it has an unknown bias.

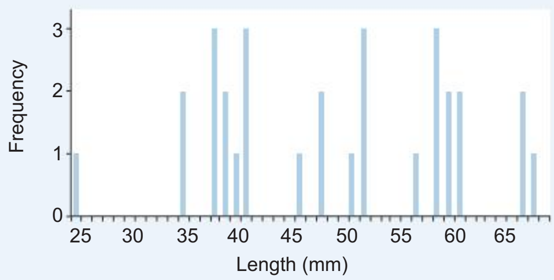
Bias refers to the selection for or against one particular group in such as way it can influence the findings of an investigation. Bias can occur when sampling is not random, and certain members of a population are under- or over-represented relative to others in the population. Small sample sizes can also bias the results, which may then not accurately reflect the population as a whole. Bias can be reduced by **random sampling** (sampling in which all members of the population have the same chance of being selected). Using appropriate collection methods and apparatus can also reduce bias.

Figure 1. Frequency histogram for the complete perch data set (N= 689)



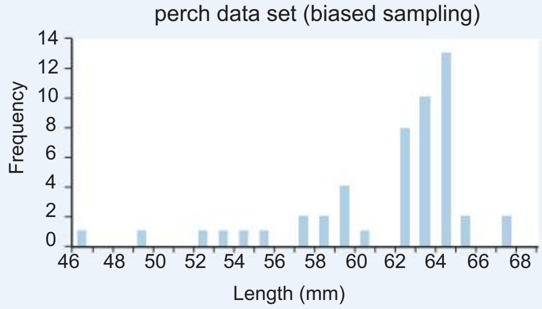
Mean: 48 mm
Median: 47 mm
Mode: 45 mm
Standard deviation: 7.81

Figure 2. Frequency histogram for the N=30 perch data set (random sampling)



Mean: 49.23 mm
Median: 49.5 mm
Mode: 38 mm
Standard deviation: 11.37

perch data set (biased sampling)



Mean: 61.44 mm
Median: 63 mm
Mode: 64 mm
Standard deviation: 3.82

- In this exercise, perch were collected and their body lengths (mm) were measured. Data are presented as a frequency histogram and with descriptive statistics (mean, median, mode and standard deviation).
- Figure 1 shows the results for the complete data set. The sample set was large (N= 689) and the perch were randomly sampled. The data are close to having a normal distribution.
- Figures 2 and 3 show results for two smaller sample sets drawn from the same population. The data collected in Figure 2 were obtained by random sampling but the sample was relatively small (N = 30). The person gathering the data displayed in Figure 3 used a net with a large mesh size to collect the perch.

1. (a) Compare the results for the two small data sets (Figures 2 and 3). How close are the mean and median to each other in each sample set?

(b) Compare the standard deviation for each sample set:

(c) Describe how each of the smaller sample sets compares to the large sample set (Figure 1):

(d) Why do you think the two smaller sample sets look so different to each other?

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18 Statistical Tests: Which One to Use?

Key Idea: How your data is analysed depends on the type of data you have collected. Plotting your initial data can help you to decide what statistical analysis to carry out.

Data analysis provides information on the biological significance of your investigation. Never under-estimate the value of plotting your data, even at a very early stage. This will help you decide on the best type of data analysis. Sometimes, statistical analysis may not be required.

START HERE

What kind of data are you recording?

Measurements or counts

Calculate mean and 95% confidence intervals from replicates

What kind of test?

Testing for a **relationship** between variables

Trend

Plot a **scatter graph**

Finding how one factor affects another

Linear regression

The data plot in a straight line.

Example: Clutch size vs body size in *Daphnia*.

Non-linear regression

The data do not plot in a straight line.

Example: Enzyme reaction rate at different temperatures.

Testing for a correlation

Normal data

Pearson correlation coefficient

Example: Arm length vs leg length.

Non-normal data

Spearman correlation coefficient

Example: Frequency of occurrence of different species at two sites.

Testing for a **difference** between groups (e.g. habitats or treatments)

Difference

Plot a **bar graph**

More than two groups of data

ANOVA (Analysis of variance)

Example: Survival of clover weevils in different pasture types.

Two groups of data

Normal data

Same individuals

Paired *t*-test

Example: Comparing ratios of arm to leg length in chimps and gorillas.

Different individuals

Unpaired *t*-test

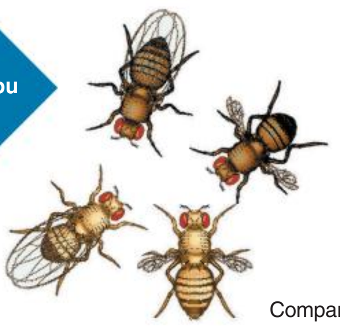
Example: Suitability of clay pots and plastic pots for plant growth.

Non-normal data

Mann-Whitney *U*-test

Data must be ranked in order of increasing size.

Example: Size of fruit from a plant species grown in two environments.



Frequencies (counts only, **not** measurements)

Test for significance of observed vs expected

Comparing observed counts to an expected count

Chi-squared for goodness of fit

Example: An expected genetic ratio or preference for different habitats.

Testing an association between groups of counts

Chi-squared for independence

Example: Association of one plant with another in an area.

Covered in QCE books 1&2

Covered in the Teacher's Digital Edition (including spreadsheets)

Covered in QCE book 1

Not required

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19 Linear Regression

Key Idea: A linear regression is an analysis of linear (straight-line) relationships between two variables where it is likely there is a cause and effect relationship.

Regression is a test for an association, relationship, or trend between two variables. It is suitable for continuous data when you have a reason to believe that the changes in one variable cause changes in the other, i.e. regression assumes a cause and effect. A regression is also predictive; the regression equation will be able to predict unknown values of the Y variable within the range covered by the data. Linear regression is the simplest functional relationship of one variable to another. If your data are appropriate for this analysis, they will plot as a straight line spread on a scatter graph. It is best to perform your regression on the raw data, because information is lost when the calculation is performed on mean values.

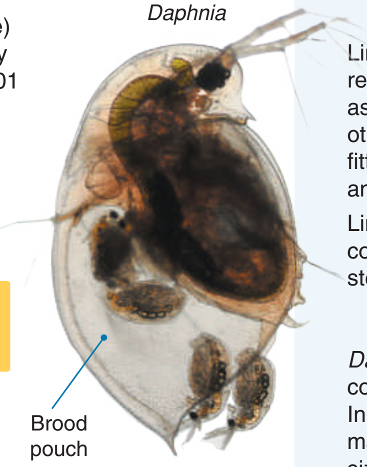
1 Enter the data

Clutch size (number of eggs per female) was estimated for 50 females, and body length was measured to the nearest 0.01 mm for the same individuals to give 50 paired values. These data values were entered directly into *Microsoft Excel®*.

	A	B
1	Body length (mm)	Clutch size
2	0.45	4
3	0.48	4
4	0.51	7
5	0.54	6
6	0.57	9
7	0.6	11
8	0.62	9
9	0.66	13
10	0.67	12
11	0.72	15
12	0.74	14
13	0.78	16
14	0.81	15
15	0.83	18
16	0.87	16
17	0.92	22
18	0.93	20
19	0.96	23
20	0.97	18
21	1.02	25
22	1.06	22
23	1.08	26
24	1.11	27
25	1.16	22
26	1.17	26
27	1.2	30
28	1.22	29
29	1.26	33
30	1.29	28
31	1.32	33
32	1.37	35
33	1.38	36
34	1.41	35
35	1.44	32
36	1.46	32
37	1.5	39
38	1.53	39
39	1.56	37
40	1.6	43
41	1.62	36
42	1.65	39
43	1.67	40
44	1.71	42
45	1.73	40
46	1.77	43
47	1.8	40
48	1.83	49
49	1.88	47
50	1.89	54
51	1.93	49
52		

Enter your data in columns with headings for the variables.

Daphnia



Linear regression

Linear regression is an analysis for a simple relationship where a change in one variable is associated with a corresponding change in the other variable in a simple linear fashion. A line is fitted to the data and gives the values of the slope and intercept of the line (the computer does this).

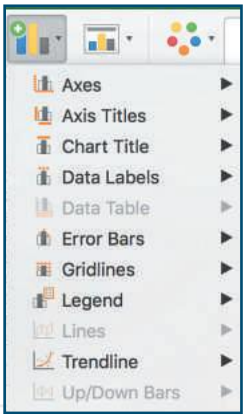
Linear regressions are simple to perform using a computer program such as *Microsoft Excel®*. The steps for doing this are outlined here.

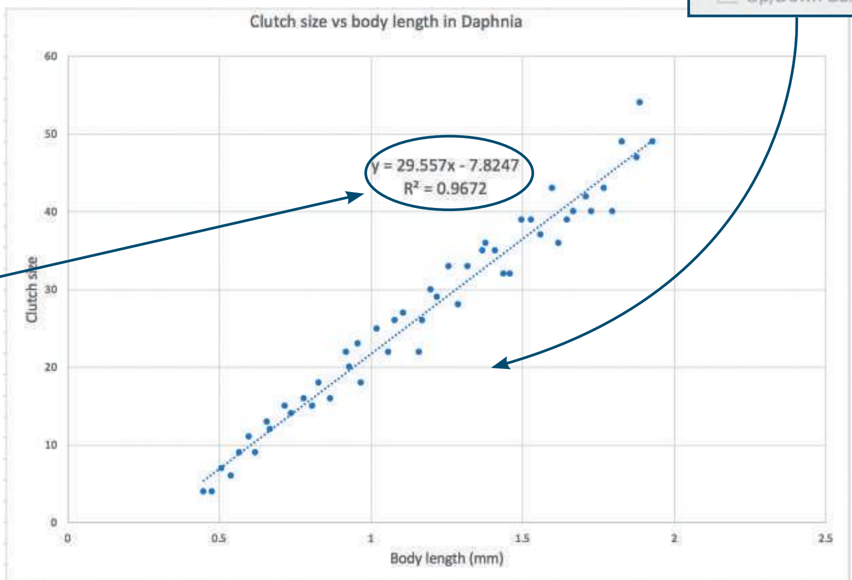
Clutch size vs body size in *Daphnia*

Daphnia is a small, freshwater crustacean common in water bodies throughout the world. In *Daphnia*, body size largely determines how many eggs and young can bee carried (the clutch size). This is because the eggs are carried in a brood pouch, which physically limits the size of the clutch. Larger animals can also process more food. The relationship between body size and clutch size can be described with a regression.

2 Graphing and fitting the regression

- Select the data columns: "Body length" and "Clutch size".
- Choose Insert > Chart > XY (Scatter). Choose the option with no line. A graph will appear on screen.
- Under the menu tab "Chart Design", choose from the drop down menu under "Add Chart Element" (right) to add titles for your axes and add a trendline (this is your regression line)
- Right click on the regression line itself to format the trendline. You can add the R^2 value and regression equation if you wish.
- The R^2 value describes how well the line fits the data. A value of 1 is a perfect fit. The equation describes the slope and intercept of the line. It allows you to predict values of the dependent variable.





Regression equation and R^2. The R^2 = 0.9672. This regression accounts for 96% of the scatter in the data.

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20 Quantifying Differences Using Student's *t* Test

Key Idea: Differences between two populations (or sets of data) can be tested for significance using the Student's *t* test.

The Student's *t* test is commonly used to compare two sample means, e.g. means for a treatment and a control in an experiment, or the means of some measured characteristic between two animal or two plant populations. It is a simple test and useful for distinguishing real but marginal differences between samples. Usefully, the test remains robust even when sample sizes are small. A simple example outlining the steps in the Student's *t* test is provided below. It compares data for a treatment and a control from a hypothetical experiment (the units are not relevant in this case, only the values).

Steps in performing a Student's *t* test

1 Calculate summary statistics for the two data sets

Control (A)	Treatment (B)
6.6	6.3
5.5	7.2
6.8	6.5
5.8	7.1
6.1	7.5
5.9	7.3

$n_A = 6$, $\bar{x}_A = 6.12$, $s_A = 0.496$

$n_B = 6$, $\bar{x}_B = 6.98$, $s_B = 0.475$

n_A and n_B are the number of values in the first and second data sets respectively (these do not need to be the same).

$\bar{x}$ is the mean.

s is the standard deviation (a measure of scatter in the data).

2 Set up and state your null hypothesis (H_0)

H_0: there is no treatment effect. The differences in the data sets are the result of chance and they are not really different. The alternative hypothesis is that there is a treatment effect and the two sets of data are truly different.

3 Decide if your test is one or two tailed

A one-tailed test looks for a difference only in one particular direction. A two-tailed test looks for any difference (+ or –). This tells you what section of the t table to consult. Most biological tests are two-tailed. Very few are one-tailed.

4 Calculate the *t* statistic

For our sample data above the calculated value of t is –3.09. The degrees of freedom (df) are $n_1 + n_2 - 2 = 10$.

Calculation of the t value uses the variance which is simply the square of the standard deviation (s^2). You may compute t using a spreadsheet but manual computation is not difficult (see opposite). It does not matter if the calculated t value is a positive or negative (the sign is irrelevant).

The absolute value of the t statistic (3.09) well exceeds the critical value for $P = 0.05$ at 10 degrees of freedom.

We can reject H_0 and conclude that the means are different at the 5% level of significance.

If the calculated absolute value of t had been less than 2.23, we could not have rejected H_0.

1. (a) In an experiment, data values were obtained from four plants in experimental conditions and three plants in control conditions. The mean values for each data set (control and experimental conditions) were calculated. The t value was calculated to be 2.16. The null hypothesis was: "The plants in the control and experimental conditions are not different". State whether the calculated t value supports the null hypothesis or its alternative (consult t table below):

____

____

(b) The experiment was repeated, but this time using 6 control and 6 "experimental" plants. The new t value was 2.54. State whether the calculated t value supports the null hypothesis or its alternative now:

____

____

2. Explain what you understand by statistical significance:

____

____

____

____

____

Table of critical values of t at different levels of P.

Degrees of freedom	Level of Probability		
	0.05	0.01	0.001
1	12.71	63.66	636.6
2	4.303	9.925	31.60
3	3.182	5.841	12.92
4	2.776	4.604	8.610
5	2.571	4.032	6.869
6	2.447	3.707	5.959
7	2.365	3.499	5.408
8	2.306	3.355	5.041
9	2.262	3.250	4.781
10	2.228	3.169	4.587
15	2.131	2.947	4.073
16	2.120	2.921	4.015
17	2.110	2.898	3.965
18	2.101	2.878	3.922
19	2.093	2.861	3.883
20	2.086	2.845	3.850
25	2.060	2.787	3.725
30	2.042	2.750	3.646
40	2.021	2.704	3.551
50	2.009	2.678	3.496
60	2.000	2.660	3.460
100	1.984	2.626	3.390

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21 Chi-Squared Test for Goodness of Fit

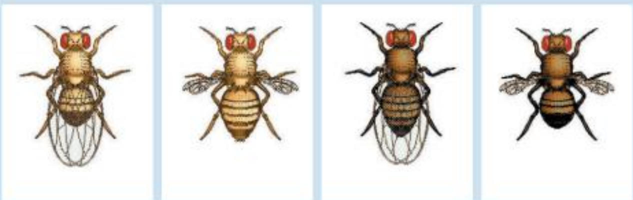
Key Idea: The chi-squared test (χ^2) for goodness of fit can be used for testing the significance of the differences between observed and expected outcomes.

The chi-squared test (χ^2), like the Student's t test, is a test for difference between data sets, but it is used when you are working with frequencies (counts) rather than measurements. The following worked example uses χ^2 to test the results of a genetic cross to see if departures from the predicted Mendelian ratio are significant. Raw counts should be used and large sample size is required for the test to be valid.

Using χ^2 in Mendelian genetics

The predicted Mendelian ratios for the offspring of a cross between two *Drosophila* flies were 1:1:1:1 for each of the four following phenotypes: grey body-long wing, grey body-vestigial wing, ebony body-long wing, ebony body-vestigial wing. The observed results of the cross were not as predicted. The following numbers for each phenotype were observed in the offspring:

Observed results (O) of the example *Drosophila* cross



98	88	102	112
Grey body, long wing	Grey body. vestigial wing	Ebony body, long wing	Ebony body, vestigial wing

Using χ^2, the probability of this result being consistent with a 1:1:1:1 ratio could be tested. Worked example as follows:

STEP 1: Calculate the expected value (E)

In this case, this is the sum of the observed values divided by the number of categories (400 ÷ 4 = 100).

STEP 2: Calculate the expected value (E)

The difference between the observed and expected values is calculated as a measure of the deviation from a predicted result. Since some deviations are negative, the are all squared to give positive values. This step is usually performed as part of a tabulation (next column, blue column).

STEP 3: Calculate the value of χ^2

The calculated χ^2 value is given at the bottom right of the last column of the table. It is calculated using the formula below.

$$\chi^2 = \sum \frac{(O-E)^2}{E}$$

The completed table is shown at the top of the next column.

Category	O	E	O – E	$(O-E)^2$	$\frac{(O-E)^2}{E}$
Grey, long wing	98	100	–2	4	0.04
Grey, vestigial wing	88	100	–12	144	1.44
Ebony, long wing	102	100	2	4	0.04
Ebony, vestigial wing	112	100	12	144	1.44
	Total = 400				χ^2 Σ = 2.96

STEP 4: Calculate the degrees of freedom

The probability that any χ^2 value would be exceeded by chance depends on the degrees of freedom. This is one less than the total number of categories (this is the number that could vary independently without affecting the last value). Here: 4 - 1 = 3.

STEP 5: Using the χ^2 table

On the χ^2 table (produced in part below) with 3 degrees of freedom, the calculated value for χ^2 of 2.96 corresponds to a probability of between 0.2 and 0.5. This means that by chance alone, a χ^2 value of 2.96 could be expected between 20% and 50% of the time.

STEP 6: Interpreting the result

The probability of between 0.2 and 0.5 is higher than the 0.05 value that is generally regarded as significant. The null hypothesis cannot be rejected and we have no reason to believe that the observed ratios obtained differ significantly from the expected at $P = 0.05$.

IMPORTANT NOTE: When analysing Mendelian crosses, predicted ratios assume independent assortment of alleles, so significant departures from predicted ratios indicate the alleles are linked (on the same chromosome). Many Mendelian crosses involve ratios other than 1:1. For these, calculation of expected values is not simply a division of the total by the number of categories. Instead, the total must be apportioned according to the ratio. For example, for a total of 400 as above and a predicted 9:3:3:1 ratio, the total count must be divided by 16 and the expected values will be 225 : 75 : 75 : 25 in each category.

Table of critical values of χ^2 at different levels of probability

By convention, the critical probability for rejecting the null hypothesis (H_0) is 5%. If the test statistic is less than the tabulated critical value for $P = 0.05$, we cannot reject H_0 and the result is not significant. If the test statistic is greater than the tabulated critical value for $P = 0.05$, we reject H_0 in favour of the alternative hypothesis.

Degrees of freedom	Level of probability (*P*)									
	0.98	0.95	0.80	0.50	0.20	0.10	0.05	0.02	0.01	0.001
1	0.001	0.004	0.064	0.455	χ^2 1.64	2.71	3.84	5.41	6.64	10.83
2	0.040	0.103	0.466	1.386	3.22	4.61	5.99	7.82	9.21	13.82
3	0.185	0.352	1.005	2.366	4.64	6.25	7.82	9.84	11.35	16.27
4	0.429	0.711	1.649	3.357	5.99	7.78	9.49	11.67	13.28	18.47
5	0.752	0.145	2.343	4.351	7.29	9.24	11.07	13.39	15.09	20.52
	← *Do not reject H_0*							*Reject H_0* →		

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22 KEY TERMS AND IDEAS: Did You Get It?

1. A balance has a calibration error of +0.04 g. A student weighs out 11.71 g of sodium hydroxide. Calculate the percentage error (show your working):

2. The table (below right) shows the rate of sweat production in an athlete on a stationary cycle.

   (a) Complete the table below to determine the rate of sweat loss in $cm^3 min^{-1}$:

   (b) Choose an appropriate graph type and plot both cumulative sweat loss and rate of sweat loss on the grid below.

Time (minutes)	Cumulative sweat loss (cm^3)	Rate of sweat loss (cm^3 min^{-1})
0	0	
10	50	
20	130	
30	220	
60	560	

   (c) Describe how the rate of sweat loss changes over time:

3. Metabolic measurements were taken from seven Antarctic fish (*Pagothenia borchgrevinski*) affected by a gill disease, which increases the thickness of the gas exchange surfaces and affects oxygen uptake. The results of oxygen consumption of active fish with varying amounts of affected gill are tabulated right.

Fish number	Percentage of gill affected	O_2 consumption (cm^3 g^{-1} h^{-1})
1	0	0.29
2	95	0.11
3	60	0.14
4	30	0.22
5	90	0.08
6	65	0.18
7	45	0.20

   (a) Plot the data on the grid below right to show the relationship between oxygen consumption and the amount of gill affected by disease. Draw a line of best fit through the data.

   (b) Using a spreadsheet programme such as Microsoft Excel:
   i) Enter the data in columns and plot an XY scatter.
   ii) Label your axes appropriately.
   iii) Plot a regression line for the data.
   iv) Display the R^2 value and the regression equation.
   v) If you wish, print the graph and staple it here.

   (c) How does the gill disease affect oxygen uptake? Use the results of your regression analysis to support your answer:

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UNIT 1
Topic 1

Cell Membrane

Key terms

active transport
carrier protein
channel protein
concentration gradient
diffusion
endocytosis
exocytosis
facilitated diffusion
hydrophilic
hydrophobic
hypertonic
hypotonic
ion
ion pump
isotonic
non-polar
osmolarity
osmosis
partially permeable (= selectively-permeable)
passive transport
phospholipid
plasma membrane
polar
plasmolysis
surface area: volume ratio
turgor

Activity number

The structure and role of the cell membrane

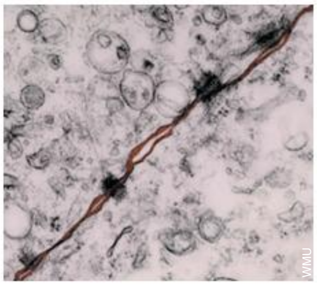
Key skills and knowledge

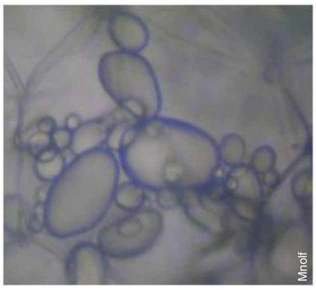
☐ 1 Describe the structure of the plasma membrane, including the phospholipid bilayer and the presence and general role of membrane proteins. Recognise that the membranes of membranous organelles have the same basic structure. **23-25**

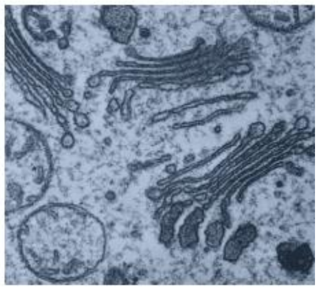
☐ 2 Describe the evidence for Singer and Nicolson's fluid mosaic model of membrane structure. How was their understanding assisted by advancements in technology? **26**

☐ 3 **SHE** Describe the ongoing research to refine the fluid mosaic model, including research into the structure of membrane proteins, e.g. channel proteins. **27**

☐ 4 Describe the role of the plasma membrane as a partially permeable boundary between the internal and external environments of the cell. Understand that it regulates the movement of substances into and out of the cell by both active and passive transport processes (see below) and know that these processes allow the cell to control its volume and obtain the materials it needs to survive. **23-25**







Passive transport across cell membranes

Key skills and knowledge

☐ 5 Describe the movement of molecules across membranes by diffusion and facilitated diffusion, identifying these as passive transport processes. Identify and explain factors affecting diffusion rates across membranes. **28-30 41**

☐ 6 **PRAC** Construct or use a model to show the selectively permeable nature of the membrane. **29 33 38**

☐ 7 Analyse data to predict the direction of movement of materials across cell membranes based on factors such as concentration and the physical and chemical nature of the materials involved. **29 33 34 38**

☐ 8 Explain the importance of surface area to volume ratio in limiting cell size. Describe the effect of decreasing SA:V ratio on how efficiently diffusion can deliver materials to the interior of cells. **30 32**

☐ 9 **PRAC** Investigate the effect of surface area to volume ratio on cell size. **31**

☐ 10 Explain the movement of water across membranes by osmosis. Understand the terms hypotonic, isotonic, and hypertonic. Explain the effects that solutions of different solute concentration can have on plant and animal cells. **33 35 41**

Active transport across cell membranes

Key skills and knowledge

☐ 11 Distinguish between passive transport and active transport, identifying the involvement of membrane proteins and energy in active transport processes. Explain how the cell membrane maintains relatively stable internal conditions by active transport of a named substance against a concentration gradient. **36-38 41**

☐ 12 Describe active transport across membrane using ion pumps, e.g. the sodium-potassium cotransporter (symport). **37 41**

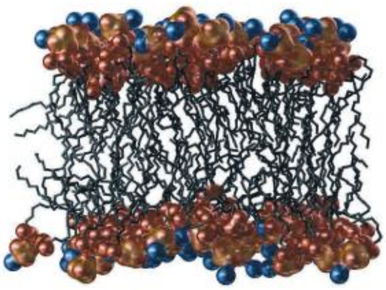
☐ 13 Distinguish between endocytosis and exocytosis, recognising both as active transport processes. Recognise the role of exocytosis in the export of materials from the cell, e.g. secretion of proteins (including enzymes) and signal molecules. **39 41**

☐ 14 Distinguish between endocytosis of fluids (pinocytosis) and solids (phagocytosis). Describe examples of when substances are moved across the plasma membrane by these mechanisms. **40 41**

23 The Plasma Membrane

Key Idea: The plasma membrane is composed of a lipid bilayer with proteins moving freely within it. It is the partially permeable (also called semi-permeable or selectively permeable) boundary between the internal and external cell environments.

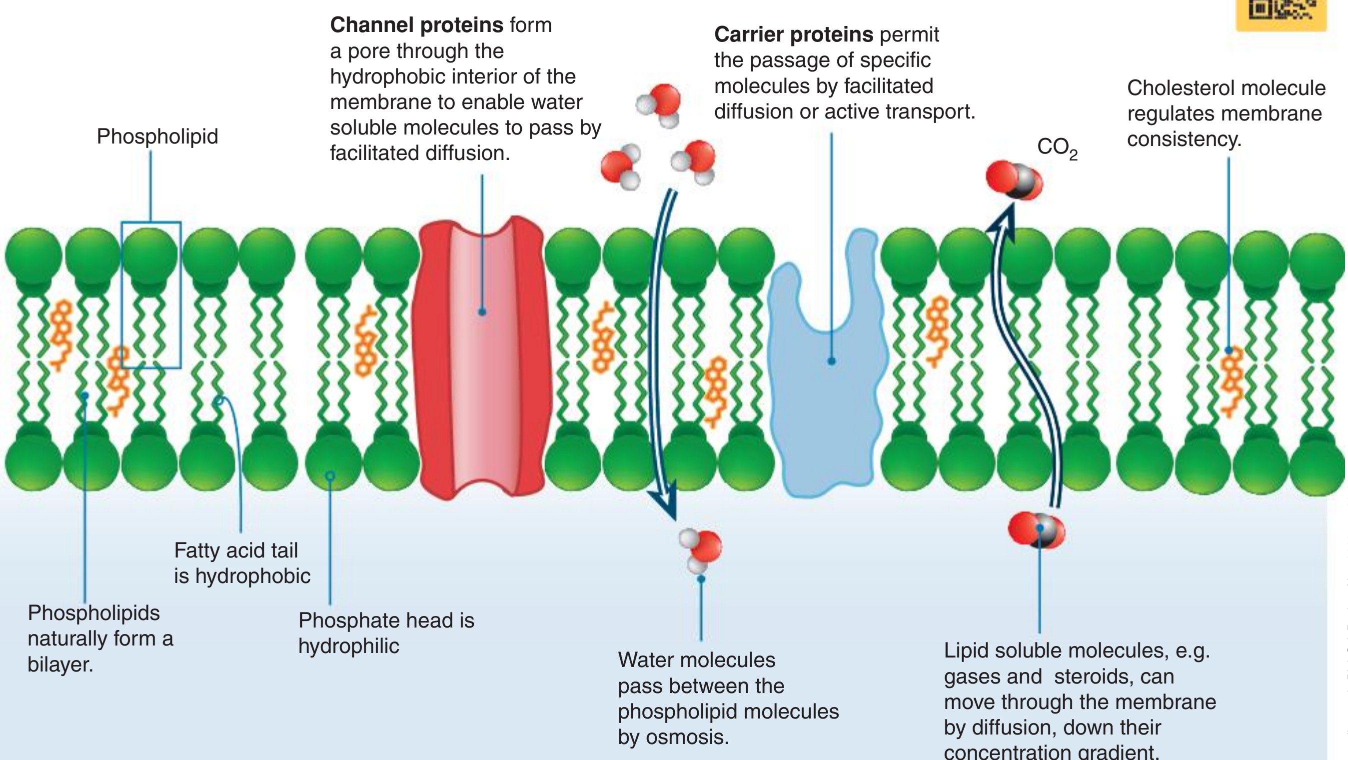
All cells have a plasma membrane, which forms the outer limit of the cell. A cell wall, if present, lies outside this, and it is quite distinct from it. Cellular membranes are also found inside eukaryotic cells as part of membranous organelles. The currently accepted model of the plasma membrane describes a lipid bilayer with proteins embedded within it, called the **fluid-mosaic model** (below). This model was devised by Singer and Nicolson in 1972. The plasma membrane is a partially permeable barrier. It allows the passage of some molecules but not others. Many of the proteins embedded in the membrane are involved in the movement of molecules by transporting specific molecules (often large molecules or ions) across the membrane, often against their concentration gradients.



Molecular model showing how phospholipid molecules naturally orientate to form a bilayer.

Simple membrane structure

External cellular environment



Internal cellular environment

Based on a diagram in Biol. Sci. Review, Nov. 2009, pp. 20-21

1. List the important components of the plasma membrane: ______________________

____

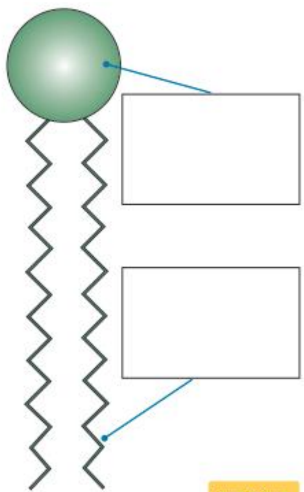
2. Identify the kind of molecule on the diagram above that:

   (a) Can move through the plasma membrane by diffusion: ______________________

   ____

   (b) Forms a channel through the membrane: ______________________

3. (a) On the diagram (right) label the hydrophobic and hydrophilic ends of the phospholipid and indicate which end is attracted to water:

   (b) How does this structure make the phospholipid molecule behave?

   ____

   ____

   ____

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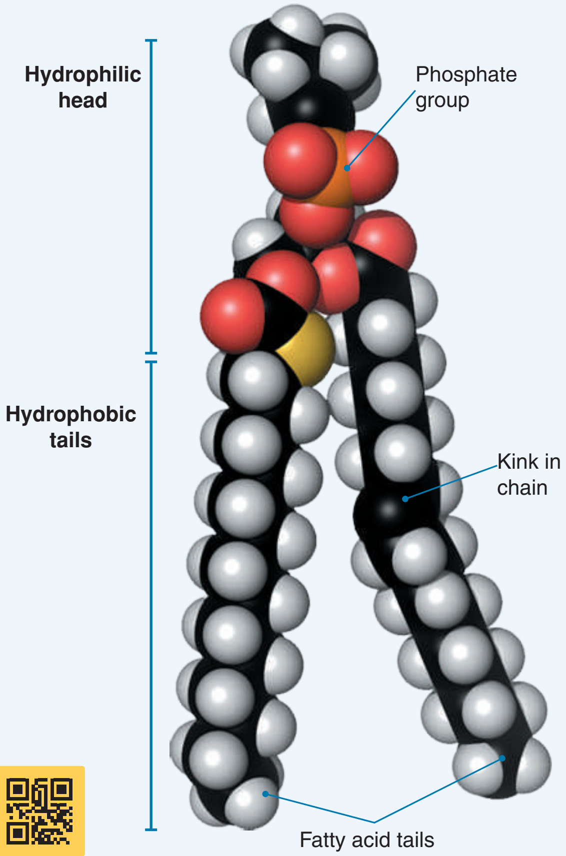
24 Phosphlipids and the Properties of Membranes

Key Idea: Phospholipids are important components of cellular membranes. They are made up of a hydrophilic head region and a hydrophobic tail region, making them amphipathic.

Phospholipids consist of a glycerol attached to two fatty acid chains and a phosphate (PO_4^{3-}) group. Phospholipids naturally form bilayers in aqueous solutions and are the main component of cellular membranes. The fatty acid tails can be saturated (forming straight chains) or unsaturated (kinked chains). The level of phospholipids with saturated or unsaturated tails affects the fluidity of the phospholipid bilayer.

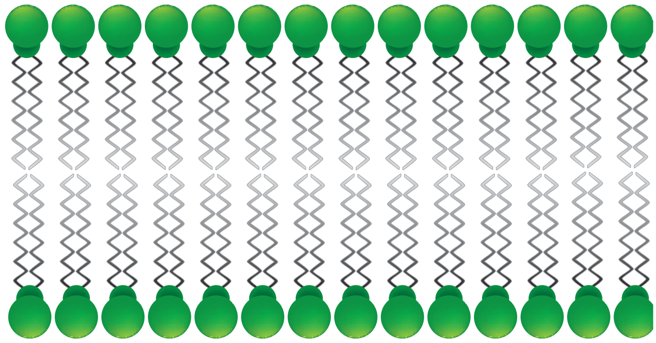
Phospholipids

The phosphate end of the phospholipid is attracted to water (it is hydrophilic) while the fatty acid end is repelled (hydrophobic). In an aqueous environment, the hydrophobic ends turn inwards in the membrane to form a bilayer. Fatty acids containing double C=C bonds are unsaturated. This causes a "kink" in the chain.

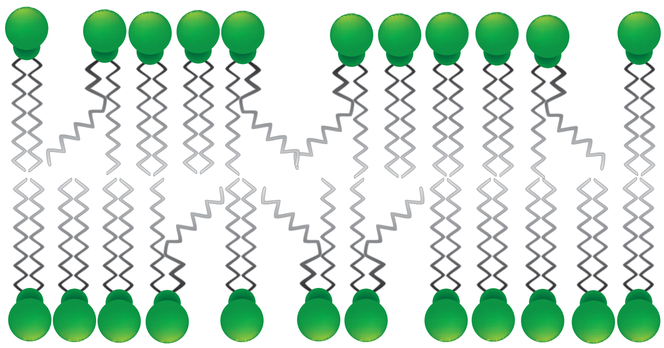


Phospholipids and membranes

Phospholipids are amphipathic (have hydrophobic and hydrophilic regions). This means that they will spontaneously form bilayers when in aqueous environments and so form the outer boundary of cells and organelles. Modifications to the hydrophobic ends of the phospholipids regulate the fluidity of the bilayer. The greater the number of double bonds in the hydrophobic tails, the greater the fluidity of the membrane.



Membrane containing only phospholipids with saturated fatty acid tails.



Membrane containing phospholipids with unsaturated fatty acid tails. The fact that the phospholipids do not stack neatly together produces a more fluid membrane that may remain fluid even at low temperatures.

1. (a) How do the properties of phospholipids contribute to their role in forming the structural framework of membranes?

(b) Explain why phospholipid bilayers containing many phospholipids with unsaturated tails are particularly fluid:

2. Suggest how the cell membrane structure of an Arctic fish might differ from that of tropical fish species:

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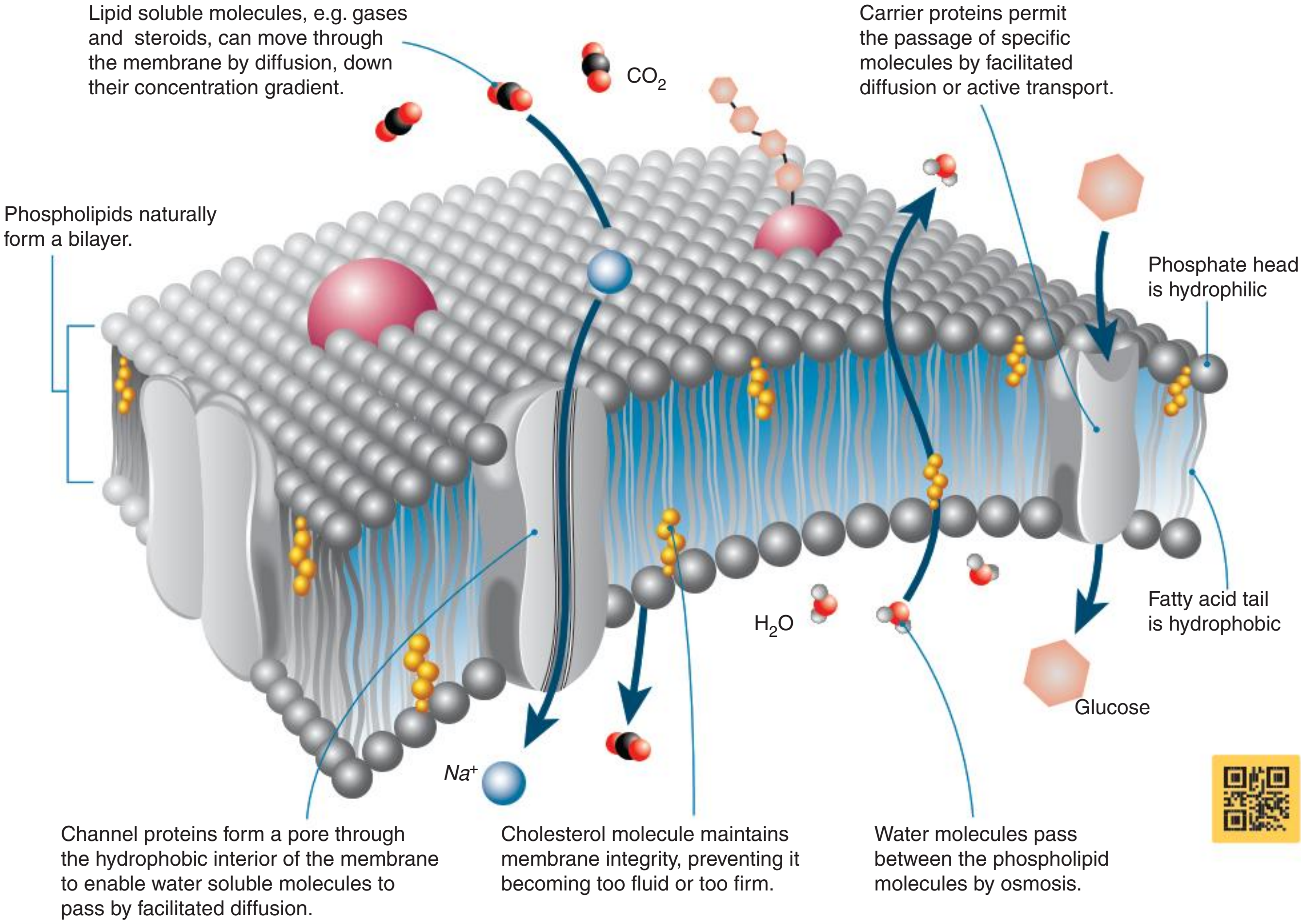
25 The Structure of the Plasma Membrane

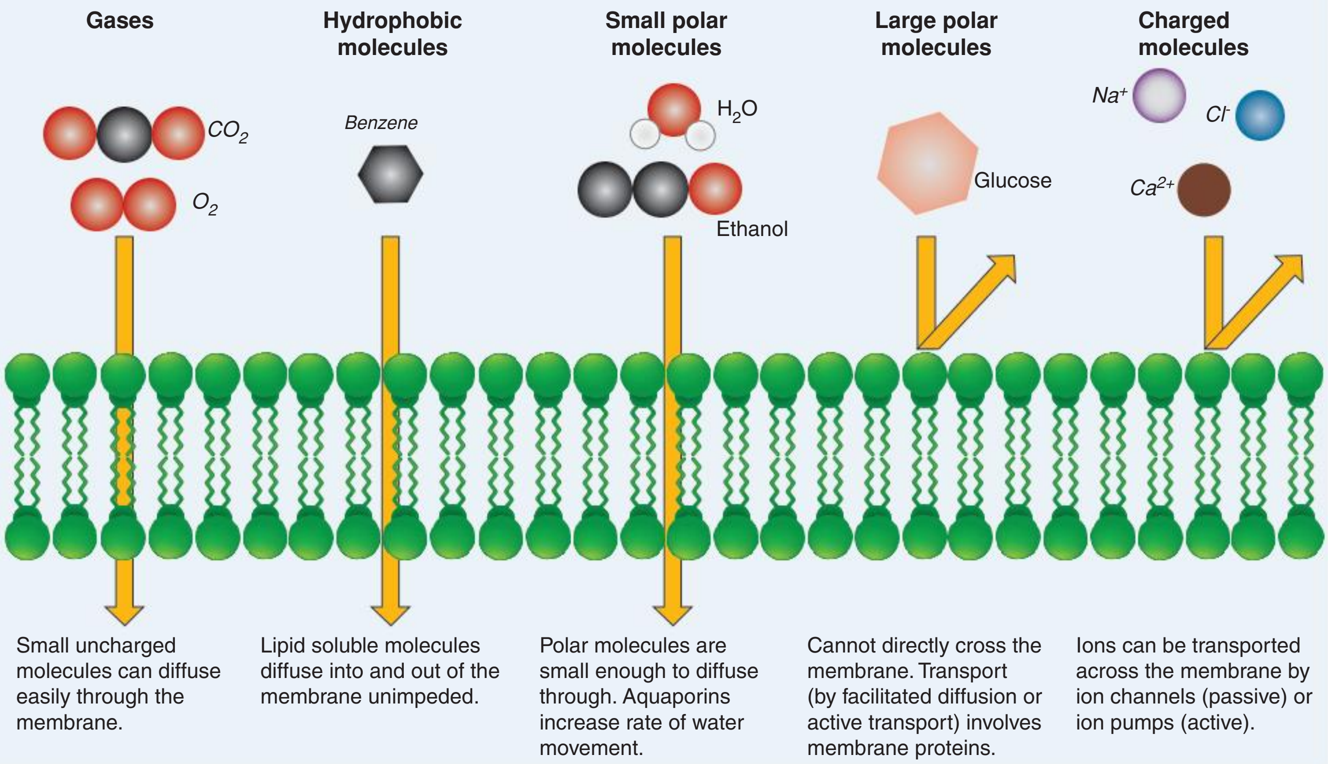
Key Idea: A cellular membrane is made of a phospholipid bilayer with proteins of different sorts embedded in it.

The cell surface (or plasma) membrane encloses the cell's contents and regulates many of the cell's activities. Importantly, it controls what enters and leaves the cell by the use of carrier and channel proteins.

Simple membrane structure



What can cross a lipid bilayer?



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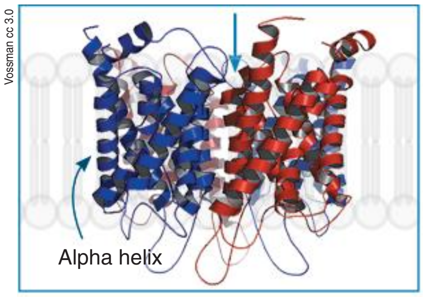
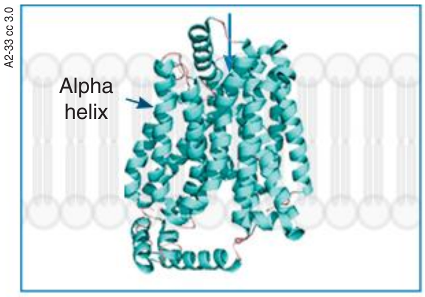
What do proteins in the cell surface membrane really look like?

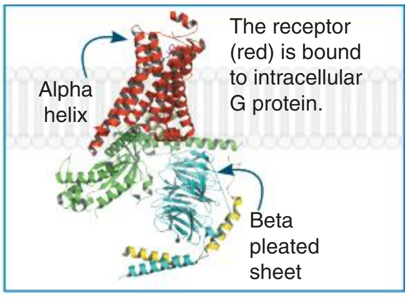
The structure of membrane proteins enables them to perform their particular function in transport, cell signalling, or cell recognition. The proteins are integral to the membrane, and often have parts of their structure projecting from both internal and external sides of the membrane. Note the two types of folding structure in membrane proteins: the alpha helix and the beta pleated sheet.



Aquaporins are a special type of channel protein that speed up the passage of water molecules across the membrane. Their tertiary structure creates a pore through the centre of the protein through which molecules can pass (arrow).



The GLUT1 glucose transporter is a carrier protein that facilitates the transport of glucose across the plasma membranes of mammalian cells. It increases the rate of glucose transport by 50,000X (high enough to supply the cell's energy needs).



G-protein coupled receptors are proteins involved in signalling pathways. A signal molecule binds to the receptor protein outside the cell to trigger a reaction involving intracellular G protein. In this example, the receptor binds to adrenaline.

1. What is the purpose of carrier proteins in the membrane? ______________________

2. What is the purpose of channel proteins in the membrane? ______________________

3. Identify the molecule(s) that:

   (a) Can diffuse through the plasma membrane on their own: ______________________

   (b) Can diffuse through the membrane via channel proteins: ______________________

   (c) Must be transported across the membrane by carrier proteins: ______________________

4. Describe the role of the following proteins in the plasma membrane:

   (a) Aquaporins: ______________________

   (b) GLUT1 protein: ______________________

   (c) G protein: ______________________

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26 How Do We Know? Membrane Structure

Key Idea: The freeze-fracture technique for preparing and viewing cellular membranes has provided evidence to support the fluid mosaic model of the plasma membrane.

Cellular membranes play many extremely important roles in cells and understanding their structure is central to understanding cellular function. Moreover, understanding the structure and function of membrane proteins is essential to understanding cellular transport processes, and cell recognition and signalling. Cellular membranes are far too small to be seen clearly using light microscopy, and certainly any detail is impossible to resolve. Since early last century, scientists have known that membranes were composed of a lipid bilayer with associated proteins. The original model of membrane structure, proposed by Davson and Danielli, was the unit membrane (a lipid bilayer coated with protein). This model was later modified by Singer and Nicolson after the discovery that the protein molecules were embedded *within* the bilayer rather than coating the outside. But how did they find out just how these molecules were organised?

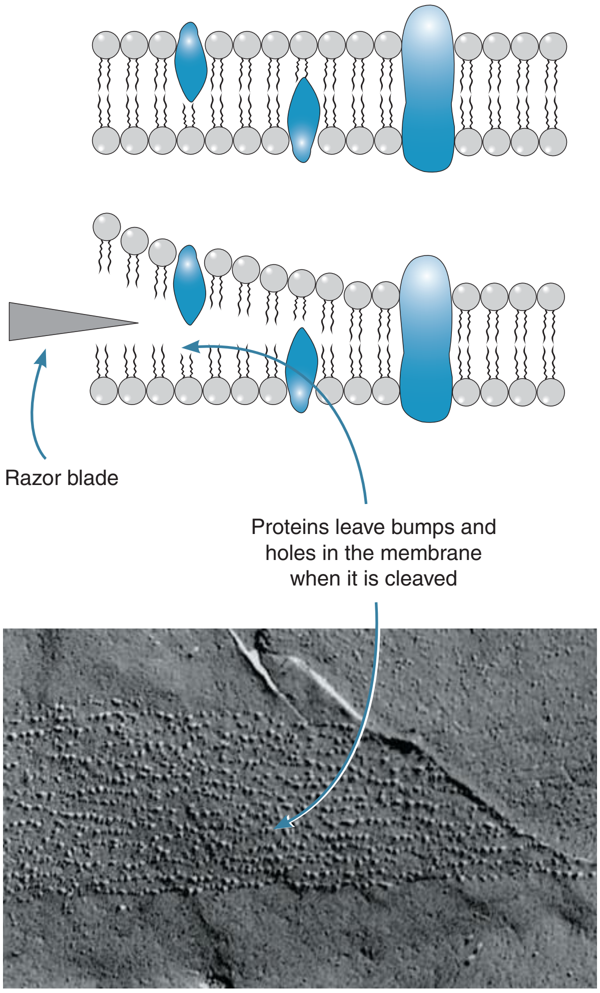
The answers were provided with electron microscopy, and one technique in particular – **freeze fracture**. As the name implies, freeze fracture, at its very simplest level, is the freezing of a cell and then fracturing it so the inner surface of the membrane can be seen using electron microscopy. Membranes are composed of two layers of phospholipids held together by weak intermolecular bonds. These split apart during fracture.

The procedure involves several steps:

- Cells are immersed in chemicals that alter the strength of the internal and external regions of the plasma membrane and immobilise any mobile macromolecules.
- The cells are passed through a series of glycerol solutions of increasing concentration. This protects the cells from bursting when they are frozen.
- The cells are mounted on gold supports and frozen using liquid propane.
- The cells are fractured in a helium-vented vacuum at -150. A razor blade cooled to -170°C acts as both a cold trap for water and the fracturing instrument.
- The surface of the fractured cells may be evaporated a little to produce some relief on the surface (known as etching) so that a three-dimensional effect occurs.
- For viewing under an electron microscope (EM), a replica of the cells is made by coating them with gold or platinum to ~3 nm thick. A layer of carbon around 30 nm thick is used to provide contrast and stability for the replica.
- The samples are then raised to room temperature and placed into distilled water or digestive enzymes, which separates the replica from the sample. The replica is then rinsed in distilled water before it is ready for viewing.

The freeze fracture technique provided the necessary supporting evidence for the current fluid mosaic model of membrane structure. When cleaved, proteins in the membrane left impressions that showed they were embedded into the membrane and not a continuous layer on the outside as earlier models proposed.

Cleaving the membrane



50 nm — Photo: Louisa Howard and Chuck Daghlian, Dartmouth College

1. Explain how freeze-fracture studies provided evidence for our current model of membrane structure: ____________________

2. The Davson and Danielli model of membrane structure was the unit membrane; a phospholipid bilayer with a protein coat. Explain how the freeze-fracture studies showed this model to be flawed:

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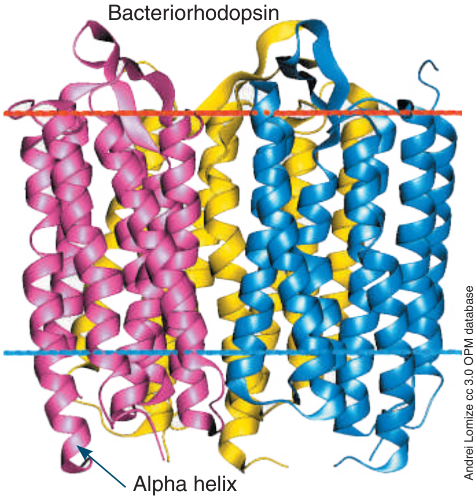
27 Cell Membrane Research

Key Idea: Research exploring the structure and function of channel proteins allows researchers to design membrane proteins with specific functions.

For the most part, the fluid mosaic model has generally proven to be correct. However, over time as technology has improved, scientists have been able to study the components in more detail and a greater understanding of the model has developed. An area of particular focus has been the protein components, including the structure and function of channel proteins. This information is valuable in understanding how the structure of a channel protein regulates the passage of molecules across the membrane. This knowledge can then be applied to the building of specific proteins with particular characteristics.

The contribution of Henderson and Unwin

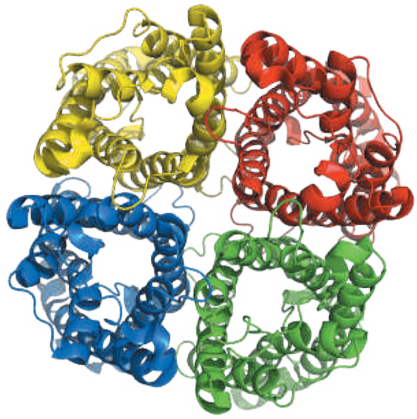
Henderson and Unwin are two important contributors to membrane research and helped to refine the fluid mosaic model to incorporate a deeper understanding of membrane proteins. They are well known for their work on bacteriorhodopsin, a protein found in the purple membrane of Archaean cells. They were the first to provide the structure of a membrane protein *in situ* (in place) using electron microscopy. Their work (1975) revealed that the protein, which consists of three units, each made up of 7 α-helices (right), spanned the membrane. This was a major step in determining the structural make-up of membrane proteins.



Bacteriorhodopsin acts as a light-driven proton pump in *Halobacterium salinarum*, converting light energy into a proton gradient, which is used to generate ATP.

Studying channel proteins

Aquaporins are channel proteins that transport water across membranes. The first reported aquaporin, in 1986, was from the human red blood cell (RBC) membrane. Its function was discovered by selectively radiolabelling RBC membrane proteins with a water transport inhibitor. With the inhibitor present, water transport stopped, identifying the protein's role as a water channel. The structure of aquaporin was revealed some time later as four bundles of six α-helices. embedded in the cell membrane (below, right) surrounding a narrow channel. Supercomputer simulations identified the pathway of water through the channel. This research has been important in understanding the role of aquaporins in increasing the permeability of membranes to water.



Aquaporin tetramer (4 units) viewed from the extracellular side. The pore is in the centre.

Future applications

Membrane proteins are relatively hydrophobic and their flexibility can make them unstable, so it can be difficult to extract them from the membrane in which they are embedded. These properties have made it difficult to study them. However, better imaging techniques and greater computing power have provided more detail about the structure and function of membrane proteins.

- Computer programmes can now be used to predict how a membrane protein will fold once it has been synthesised. This has allowed molecular engineers to design and build artificial membrane proteins.
- One application of this is to improve the delivery of therapeutic drugs to target receptors (often membrane proteins). Building a protein allows researchers to study how a drug interacts with its target, and provides an opportunity to modify the drug for increased effectiveness.
- Another approach is to design new proteins with specific functions, e.g. to deliver specific substances across the membrane of a target cell.

1. Using the fluid mosaic model as an example, suggest why scientific models are often modified over time:

2. (a) Why has it been difficult to determine the structure of membrane proteins?

(b) Explain the role in technological developments in furthering our understanding of membrane proteins:

SHE 1

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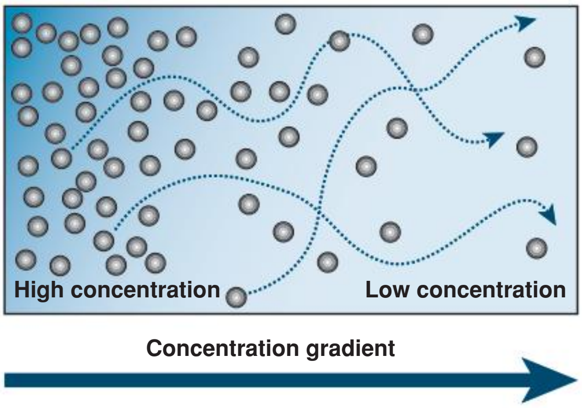
28 Diffusion

Key Idea: Diffusion is the movement of molecules from higher concentration to a lower concentration (i.e. down a concentration gradient).

The molecules that make up substances are constantly moving about in a random way. This random motion causes molecules to disperse from areas of high to low concentration. This dispersal is called **diffusion** and it requires no energy. Each type of molecule moves down its own concentration gradient. Diffusion is important in allowing exchanges with the environment and in the regulation of cell water content.

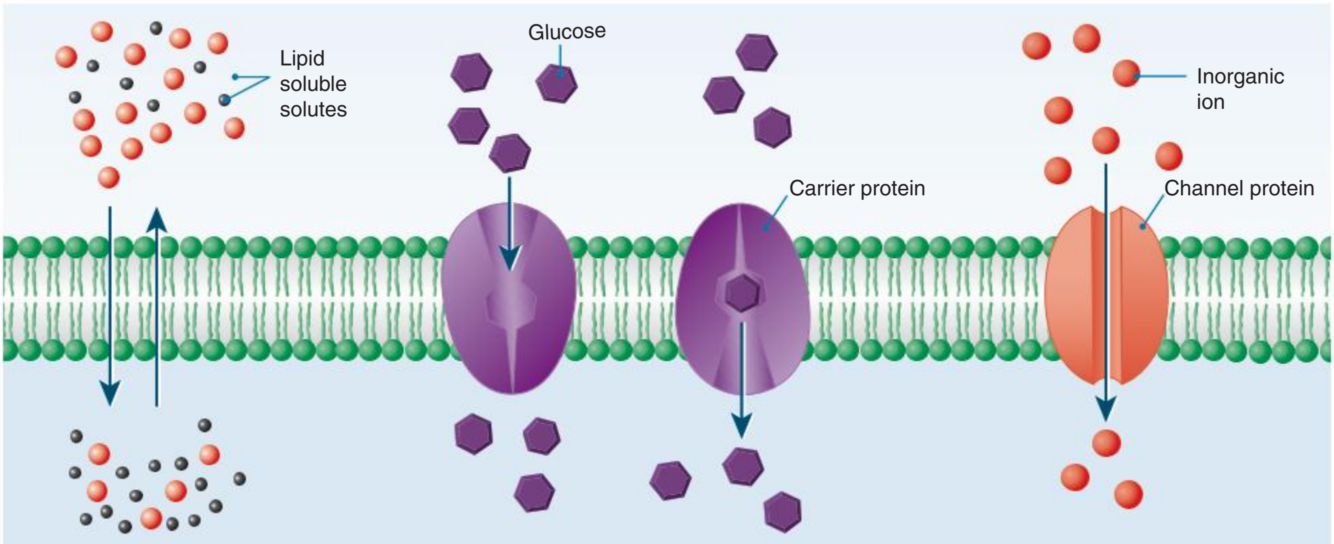
What is diffusion?

Diffusion is the movement of particles from regions of high concentration to regions of low concentration (down a concentration gradient). Diffusion is a **passive process**, meaning it needs no input of energy to occur. During diffusion, molecules move randomly about, becoming evenly dispersed.



Factors affecting the rate of diffusion

Concentration gradient	The rate of diffusion is higher when there is a greater difference between the concentrations of two regions.
The distance moved	Diffusion over shorter distance occurs at a greater rate than over a larger distance.
The surface area involved	The larger the area across which diffusion occurs, the greater the rate of diffusion.
Barriers to diffusion	Thick barriers have a slower rate of diffusion than thin barriers.
Temperature	Particles at a high temperature diffuse at a greater rate than at a low temperature.



Simple diffusion
Molecules move directly through the membrane without assistance. Example: O_2 diffuses into the blood and CO_2 diffuses out.

Carrier-mediated facilitated diffusion
Carrier proteins allow large lipid-insoluble molecules that cannot cross the membrane by simple diffusion to be transported into the cell. Example: the transport of glucose into red blood cells.

Channel-mediated facilitated diffusion
Channels (hydrophilic pores) in the membrane allow inorganic ions to pass through the membrane. Example: K^+ ions exiting nerve cells to restore resting potential.

1. What do the three types of diffusion described above all have in common? ______________________

____

2. How does facilitated diffusion differ from simple diffusion? ______________________

____

____

____

____

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29 Investigating Diffusion

Key Idea: Dialysis tubing can be used to model the diffusion of glucose down its concentration gradient.

Diffusion through a partially permeable membrane can be modelled using dialysis tubing. The pores of the dialysis tubing determine the size of the molecules that can pass through. The experiment described below demonstrates how glucose will diffuse down its concentration gradient from a high glucose concentration to a low glucose concentration.

The aim

To demonstrate diffusion through a selectively permeable membrane.

Hypothesis

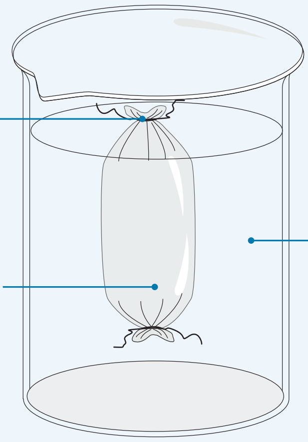
If there is no glucose outside the dialysis tubing, then glucose will diffuse down its concentration gradient from the dialysis tubing into the distilled water until the glucose concentrations are equal.

Background

Dialysis tubing acts as a partially (or selectively) permeable membrane. It comes in many pore sizes and only allows molecules smaller than the size of the pore to pass through.

Lugol's indicator contains iodine, and turns blue/black in the presence of starch.

The presence of glucose can be tested using a glucose dipstick test. If glucose is present, the indicator window will change colour. The colour change can be compared against a reference to determine the concentration of glucose present.



Method

Dialysis tubing was filled with 5 cm^3 each of a 1% starch solution and a 10% glucose solution. A 1 cm^3 sample was removed and tested for the presence of starch using Lugol's indicator, and glucose using a glucose dipstick.

The dialysis tubing was tied, and the outside of the tubing washed with distilled water to remove any starch or glucose that spilled on to the outer surface during filling. The tubing was placed into a beaker of distilled water.

After 30 minutes, the solution inside the dialysis tubing and the distilled water were tested for the presence of starch and glucose.

1. Why was it important to wash the dialysis tubing before placing it into the beaker of distilled water? ______________

____

2. What part of a cell does the dialysis tubing represent?

____

3. The results for the experiment are tabulated right.

	Dialysis tubing start	Beaker start	Dialysis tubing end	Beaker end
Starch	++	-	++	-
Glucose	++	-	+	+

● Starch ● Glucose

(a) In the spaces provided (below, right) draw the distribution of starch and glucose at the start and at the end of the experiment. Use the coloured symbols shown under the table to represent starch and glucose:

Dialysis tubing start	Beaker start

Dialysis tubing end	Beaker end

(b) Describe why glucose has moved across the partially permeable membrane during the experiment:

____

____

____

____

(c) Why was there no starch present in the beaker at the end of the experiment?

____

____

____

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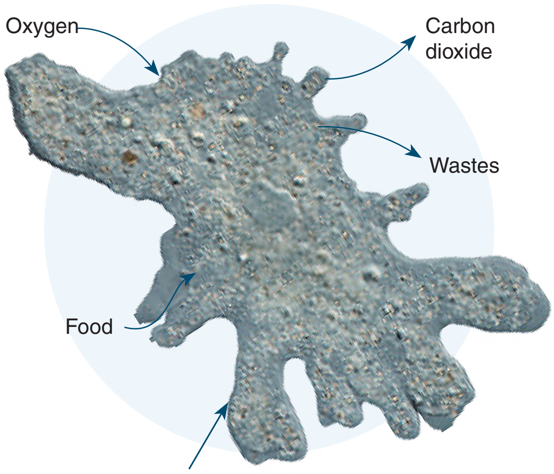
30 Diffusion and Cell Size

Key Idea: Diffusion is less efficient in cells with a small surface area relative to their volume than in cells with a large surface area relative to their volume.

Small objects, such as cells, have a large surface area relative to their volume and diffusion is an effective way to move materials in and out. As an object becomes larger, its surface area to volume ratio is smaller and diffusion is no longer an effective way to transport materials to the inside. The effectiveness of diffusion is therefore the controlling factor determining how big an individual cell can become. In large, multicellular organisms, specialised systems deliver materials to the many cells that make up the tissues of the body.

Single-celled organisms

Single-celled organisms (e.g. *Amoeba*), are small and have a large surface area relative to the cell's volume. The cell's requirements can be met by the diffusion or active transport of materials into and out of the cell (below).



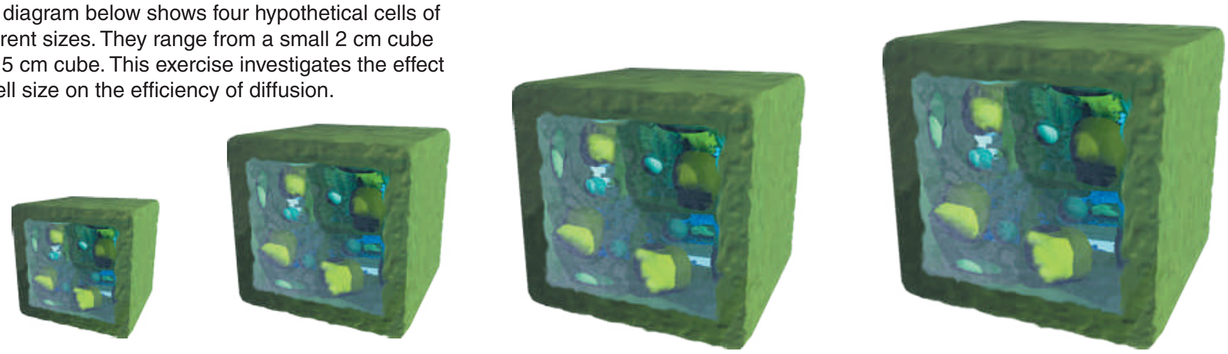
The **plasma membrane**, which surrounds every cell, regulates movements of substances into and out of the cell. For each square micrometre of membrane, only so much of a particular substance can cross per second.

Multicellular organisms

Multicellular organisms (e.g. plants and animals) generally have a small surface area compared to their volume. They require specialised body systems to transport the materials they need to and from the cells and tissues in their body.

In a multicellular organism, such as an elephant, a specialised gas exchange surface (lungs) and circulatory (blood) system transport substances to the body's cells.

The diagram below shows four hypothetical cells of different sizes. They range from a small 2 cm cube to a 5 cm cube. This exercise investigates the effect of cell size on the efficiency of diffusion.



1. Calculate the volume, surface area and the ratio of surface area to volume for each of the four cubes above (the first has been done for you). When completing the table below, show your calculations.

Cube size	Surface area	Volume	Surface area to volume ratio
2 cm cube	$2 \times 2 \times 6 = 24\ cm^2$ (2 cm x 2 cm x 6 sides)	$2 \times 2 \times 2 = 8\ cm^3$ (height x width x depth)	24 to 8 = 3:1
3 cm cube			
4 cm cube			
5 cm cube			

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31 Investigating the Effect of Cell Size

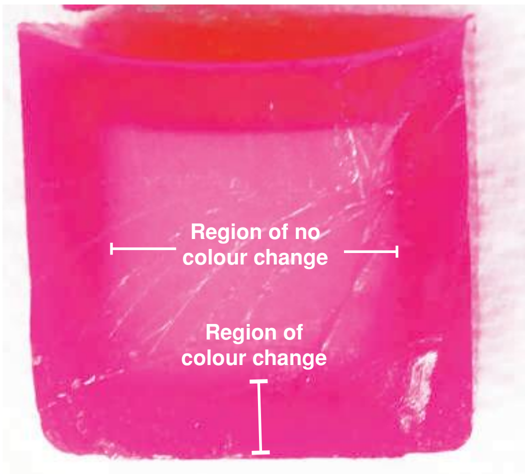
Key Idea: Diffusion is less efficient in cells with a small surface area relative to their volume than in cells with a large surface area relative to their volume.

When an object (e.g. a cell) is small it has a large surface area in comparison to its volume. Diffusion is an effective way to transport materials (e.g. gases) into and out of the cell. As an object becomes larger, its surface area compared to its volume is smaller and diffusion is no longer an effective way to transport materials to and from the inside. In this activity you will design an experiment to demonstrate the effect of surface area: volume ratios on diffusion in model cells. Think about how you will plan your investigation and analyse your data to obtain meaningful results. This will help you to make valid conclusions about your findings.

Background information

Oxygen, water, cellular waste, and many nutrients are transported into and out of cells by diffusion. However, at a certain surface area to volume ratio, diffusion becomes inefficient. In this activity you will create model cells of varying sizes from agar and use them to test the relationship between cell size and rate or efficiency of diffusion.

- The diffusion of molecules into a cell can be modelled by using agar cubes infused with phenolphthalein indicator and soaked in sodium hydroxide (NaOH).
- Phenolphthalein is an acid/base indicator and turns pink in the presence of a base.
- As the NaOH diffuses into the agar, the phenolphthalein changes to a pink colour and thus indicates how far into the agar block the NaOH has diffused (right).
- By cutting an agar block into cubes of various sizes, it is possible to investigate the effect of cell size on diffusion.



A phenolphthalein-infused agar cube after exposure to NaOH.

Equipment list

Glass beaker

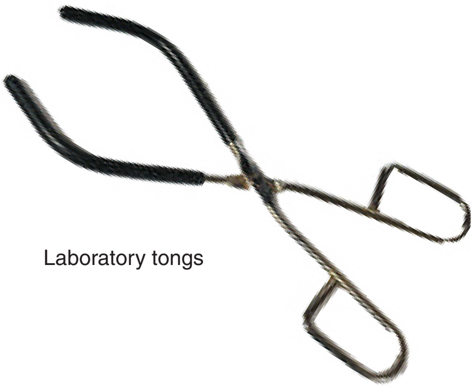
Paper towel

Timer

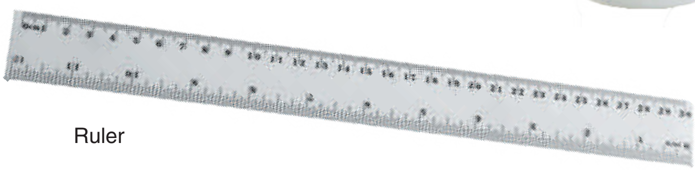
Agar blocks infused with phenolphthalein

Sodium hydroxide (NaOH) solution

Scalpel



Laboratory tongs



Ruler

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Based on the aim of this experiment "To investigate the effect of cell size on diffusion in a model cell", the background information provided, and the equipment list provided, design your own experiment using the questions below to guide you.

1. State an hypothesis for your experiment:

2. Write your method as step by step instructions:

3. In the space below draw a table to record your results. Remember to record cell volume and include space to work out how much diffusion has occurred.

4. Write your conclusions here:

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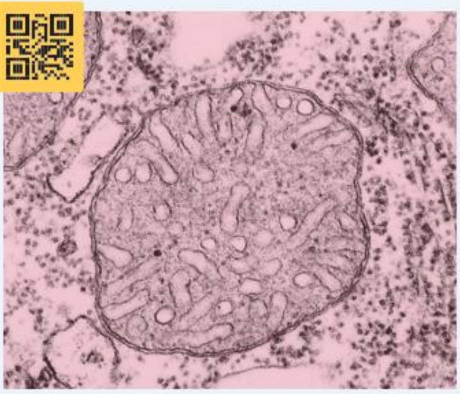
32 Overcoming Limitations to Cell Size

Key Idea: Larger cells can maintain high surface area to volume ratios by having a non-spherical shape and membrane extensions. Organelles also increase functional efficiency.

We have seen that cells must exchange materials with the extracellular environment in order to survive. The efficiency of these exchanges, which must occur across the plasma membrane, is limited by the cell's surface area to volume ratio. Larger cells can maintain higher SA:V ratios by having a non-spherical shape and extensions of the membrane. Within the cell, the presence of organelles specialised to perform particular functions creates cellular compartments, which also improve functional efficiency in a larger cell.

Cell size and functional efficiency

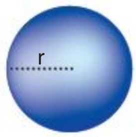
Cells have a wide range of sizes. Large eukaryotic cells may reach 100 µm in diameter, whereas bacteria typically only reach a tenth of that. Eukaryotic cells can remain efficient at larger sizes in part because they contain **organelles**, which concentrate associated materials (such as the reactants and enzymes in a metabolic pathway) into specific regions for specific purposes. These cellular compartments enable efficiency of function.



Cellular respiration occurs within the mitochondria, which has regions in which different reactions occur.

Solving the size problem

One way of increasing a cell's surface area while retaining the same volume is to elongate the cell. An elongated sphere (an ellipsoid, e.g. a rod shaped cell) has a greater surface area than a sphere of the same volume. In this way, a cell can grow larger while still gaining the materials it needs. The cells of multicellular organisms are often highly specialised to maximise SA: V. The three images below are all to scale.

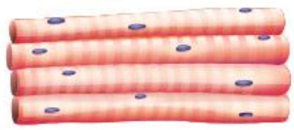


Sphere
V = 2 cm^3
SA= 7.65 cm^2

Ellipsoid
V = 2 cm^3
SA= 8.8 cm^2

Disc shaped ellipsoid
V = 2 cm^3
SA= 14.98 cm^2

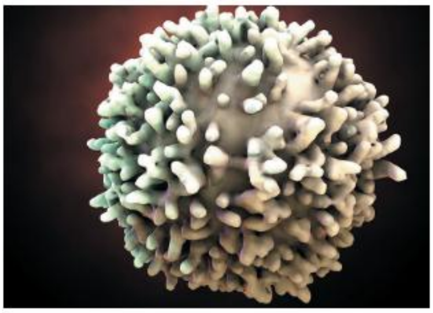
White blood cell



Skeletal muscle cells

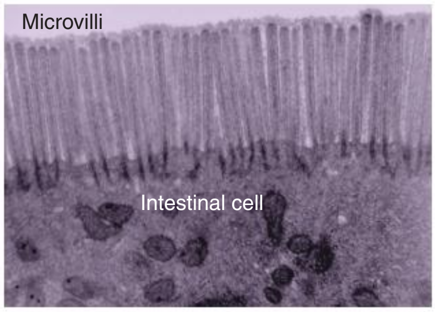
Red blood cell

By flattening the ellipsoid along one axis and stretching it along the other two to form a disc, surface area increases while the volume remains the same.



Animal cells, such as this B cell (a type of white blood cell), often have extensions of the cell membrane providing a high surface area for transfer of materials.

Tissues are organised to increase surface area. Here, the intestinal wall is folded into projections called villi. Column-shaped intestinal cells line the surface of the villi.



The cell membrane of each intestinal cell is folded into numerous microvilli. These increase the surface area for absorbing nutrient and binding digestive enzymes.

1. Use the formula $4\pi r^2$ (where π = 3.14) to calculate the surface area of a spherical cell with a radius (r) of:

   (a) 2 µm: ______________________ (c) 10 µm: ______________________

   (b) 5 µm: ______________________ (d) 30 µm: ______________________

2. (a) What happens to the SA:V ratio of a spherical cell as its volume increases? ______________________

   (b) How can eukaryotic cells overcome the restrictions of reduced SA:V as they become larger: ______________________

   ____

   ____

   ____

ISBN: 978-1-927309-83-4

33 Osmosis

Key Idea: Osmosis is the diffusion of water molecules from a lower solute concentration to a higher solute concentration across a partially permeable membrane.

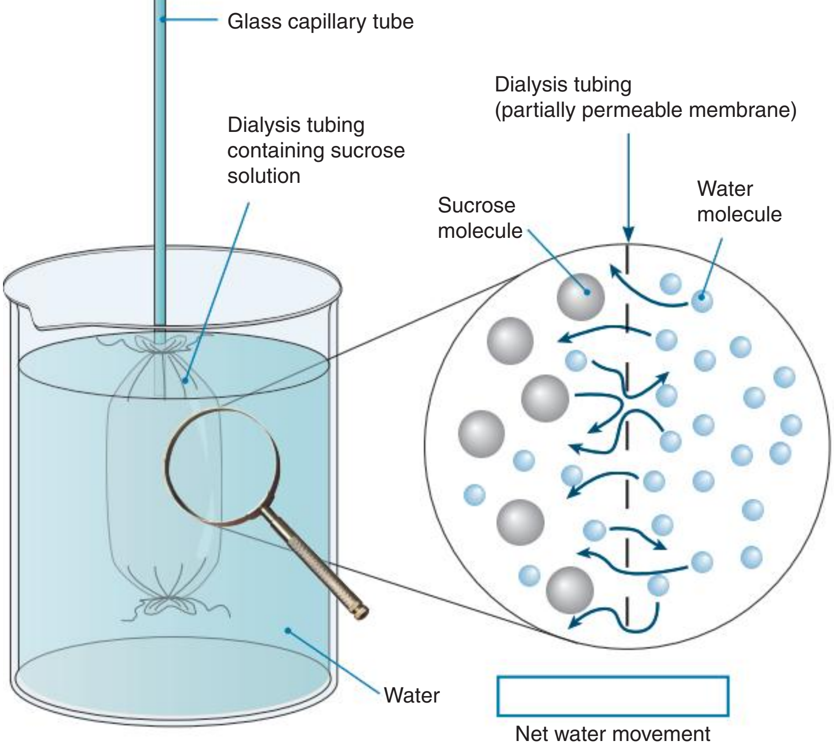
Osmosis is the diffusion of water molecules from regions of lower solute concentration (higher free water concentration) to regions of higher solute concentration (lower free water concentration) across a partially permeable membrane. A partially permeable membrane allows some molecules, but not others, to pass through. Water molecules will diffuse across a partially permeable membrane until an equilibrium is reached and net movement is zero. The plasma membrane of a cell is an example of a partially permeable membrane. Osmosis is a passive process and does not require any energy input.

Demonstrating osmosis

Osmosis can be demonstrated using dialysis tubing in a simple experiment (described below). Dialysis tubing, like all cellular membranes, is a partially permeable membrane.

A sucrose solution (high solute concentration) is placed into dialysis tubing, and the tubing is placed into a beaker of water (low solute concentration). The difference in concentration of sucrose (solute) between the two solutions creates an osmotic gradient. Water moves by osmosis into the sucrose solution and the volume of the sucrose solution inside the dialysis tubing increases.

The dialysis tubing acts as a partially permeable membrane, allowing water to pass freely, while keeping the sucrose inside the dialysis tubing.



Osmotic potential

The presence of solutes (dissolved substances) in a solution increases the tendency of water to move into that solution. This tendency is called the osmotic potential or osmotic pressure. The more total dissolved solutes a solution contains, the greater its osmotic potential.

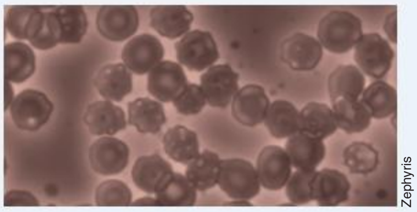
Describing solutions

Osmosis is important when handling body tissues for medical transport or preparation. The tissue must be bathed in a solution with an osmolarity (a measure of solute concentration) equal to the tissue's to avoid a loss or gain of fluid in the tissue. Solutions separated by a partially permeable membrane are often described in terms of their solute concentration concentrations relative to one another.

Isotonic solution: Having the same solute concentration relative to another solution (e.g. the cell's contents).

Hypotonic solution: Having a lower solute concentration relative to another solution.

Hypertonic solution: Having a higher solute concentration relative to another solution.



The red blood cells above were placed into a hypertonic solution. As a result, the cells have lost water and have begun to shrink, losing their usual discoid shape.

1. What is osmosis? ______________________________

____

____

2. (a) In the blue box on the diagram above, draw an arrow to show the direction of net water movement.

(b) Why did water move in this direction? ______________________________

____

____

3. What would happen to the height of the water in the capillary tube if the sucrose concentration was increased?

____

ISBN: 978-1-927309-83-4

34 Estimating Osmolarity of Cells

Key Idea: A cell placed in a hypotonic solution will gain water while a cell placed in a hypertonic solution will lose water.

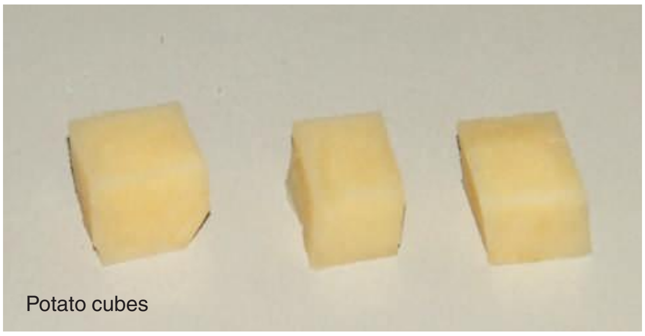
The osmolarity (a measure of solute concentration) of a cell or tissue can be estimated by placing part of the cell or tissue into a series of solutions of known concentration and observing if the tissue loses (hypertonic solution) or gains (hypotonic solution) water. The solution in which the tissue remains unchanged indicates the osmolarity of the tissue.

The aim

To investigate the osmolarity of potatoes by placing cubes of potato in varying solutions of sucrose, $C_{12}H_{22}O_{11}$ (table sugar).

The method

Fifteen identical 1.5 cm^3 cubes of potato were cut and weighed in grams to two decimal places. Five solutions of sucrose were prepared in the following range (in mol L^{-1}): 0.00, 0.25, 0.50, 0.75, 1.00. Three potato cubes were placed in each solution for two hours, stirring every 15 minutes. The cubes were then retrieved, patted dry on blotting paper and weighed again.



Kent Pryor

The results

Sucrose concentration (mol L^{-1})	Potato sample	Initial mass (I) (g)	Final mass (F) (g)
0.00	1	5.11	6.00
	2	5.15	6.07
	3	5.20	5.15
Total			
Change (C) (F-I) (g)			
% Change (C/I x 100)			
0.25	1	6.01	4.98
	2	6.07	5.95
	3	7.10	7.00
Total			
Change (C) (F-I) (g)			
% Change (C/I x 100)			
0.50	1	6.12	5.10
	2	7.03	6.01
	3	5.11	5.03
Total			
Change (C) (F-I) (g)			
% Change (C/I x 100)			
0.75	1	5.03	3.96
	2	7.10	4.90
	3	7.03	5.13
Total			
Change (C) (F-I) (g)			
% Change (C/I x 100)			
1.00	1	5.00	4.03
	2	5.04	3.95
	3	6.10	5.02
Total			
Change (C) (F-I) (g)			
% Change (C/I x 100)			

1. Complete the table (left) by calculating the total mass of the potato cubes, the total change in mass, and the total % change in mass for all the sucrose concentrations:

2. Use the grid below to draw a line graph of the sucrose concentration vs total % change in mass:

3. Use the graph to estimate the osmolarity of the potato (the point where there is no change in mass):

4. Identify which of the solutions are hypotonic and which are hypertonic.

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35 Water Relations in Plant Cells

Key Idea: Plant cells in a hypertonic solution lose water and undergo plasmolysis. In a hypotonic solution, they gain water creating turgor pressure.

Osmosis across the partially permeable cell membrane is the main way by which water enters and leaves the cell. When the external concentration of free water molecules is the same as that of the cytoplasm there is no net movement of water. Changing the tonicity of the external environment will cause a net movement of water into or out of the cell as water moves down its concentration gradient.

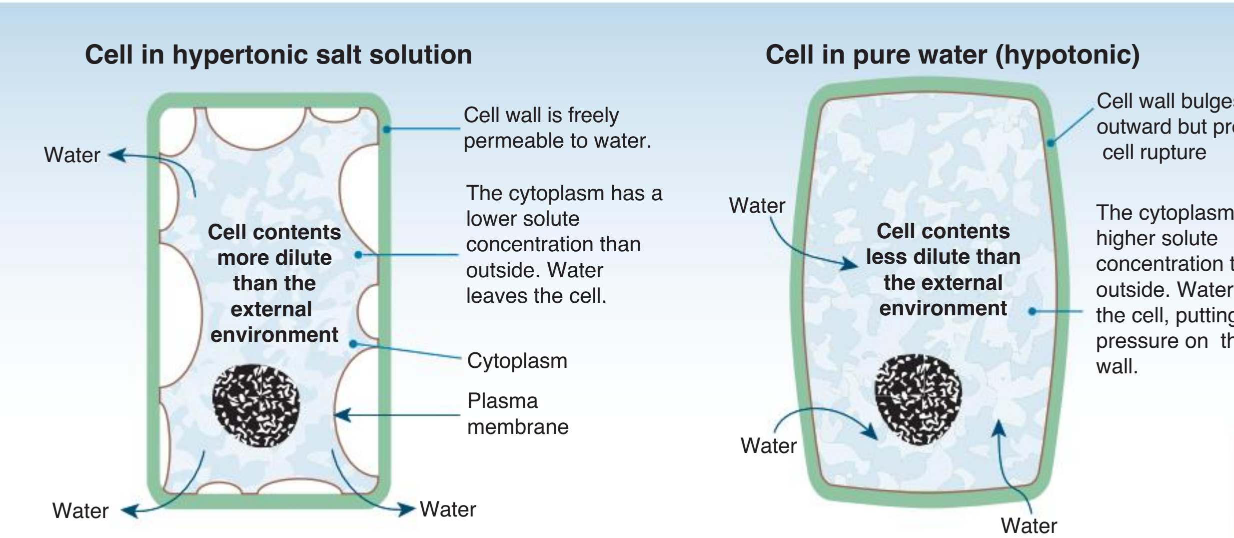
Osmosis and tonicity

When the watery contents of a plant cell push against the cell wall they create **turgor** (tightness) which helps to provide support for the plant body. When cells lose water, there is a loss of cell turgor and the plant will wilt. Complete loss of turgor from a cell is called plasmolysis and is irreversible. Two systems (cell and environment) with the same effective osmotic pressure are termed isotonic and there is no net movement of water molecules. However, when there is an osmotic gradient between the cell and environment there will be a net movement of water molecules down their concentration gradient. The diagram below shows two different situations: when a plant cell is in a hypertonic solution and when it is in a hypotonic solution.


Wilted plant (cells have lost turgor)


Plant cells are turgid

MCC UW



Plasmolysis in a plant cell

Tonicity is a measure of the osmotic pressure of a solution. In a hypertonic solution, the external free water concentration is lower than the free water concentration of the cell. Water leaves the cell and, because the cell wall is rigid, the cell membrane shrinks away from the cell wall. This is called **plasmolysis** and the cell becomes flaccid.

Turgor in a plant cell

In a hypotonic solution, the external free water concentration is higher than the cell cytoplasm. Water enters the cell, causing it to swell tight. A wall (turgor) pressure is generated when the cell contents press against the cell wall. Turgor pressure increases until no more water enters the cell (the cell is **turgid**).

1. Identify the outcome of the following situations:

   (a) A plant cell is placed in a hypertonic solution: ______________________

   (b) A plant cell is placed in a hypotonic solution: ______________________

   (c) A plant cell in an isotonic solution: ______________________

2. (a) Explain the role of cell wall pressure in generating cell turgor in plants: ______________________

   ____

   ____

   (b) Discuss the role of cell turgor in plants: ______________________

   ____

   ____

   ____

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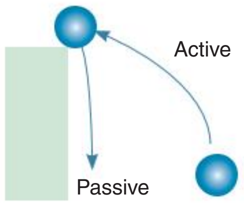
36 Active Transport

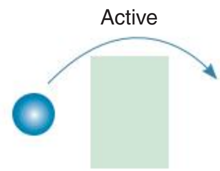
Key Idea: Active transport uses energy to transport molecules against their concentration gradient across a partially permeable membrane.

Active transport is the movement of molecules (or ions) from regions of low concentration to regions of high concentration across a cellular membrane by a transport protein. Active transport needs energy to proceed because molecules are being moved against their concentration gradient.

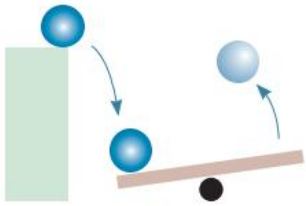
- The energy for active transport comes from ATP (adenosine triphosphate). Energy is released when ATP is hydrolysed (water is added) forming ADP (adenosine diphosphate) and inorganic phosphate (Pi).
- Transport (carrier) proteins in the membrane are used to actively transport molecules from one side of the membrane to the other (below).
- Active transport can be used to move molecules into and out of a cell.
- Active transport can be either primary or secondary. Primary active transport directly uses ATP for the energy to transport molecules. In secondary active transport, energy is stored in a concentration gradient. The transport of one molecule is coupled to the movement of another down its concentration gradient, ATP is not directly involved in the transport process.



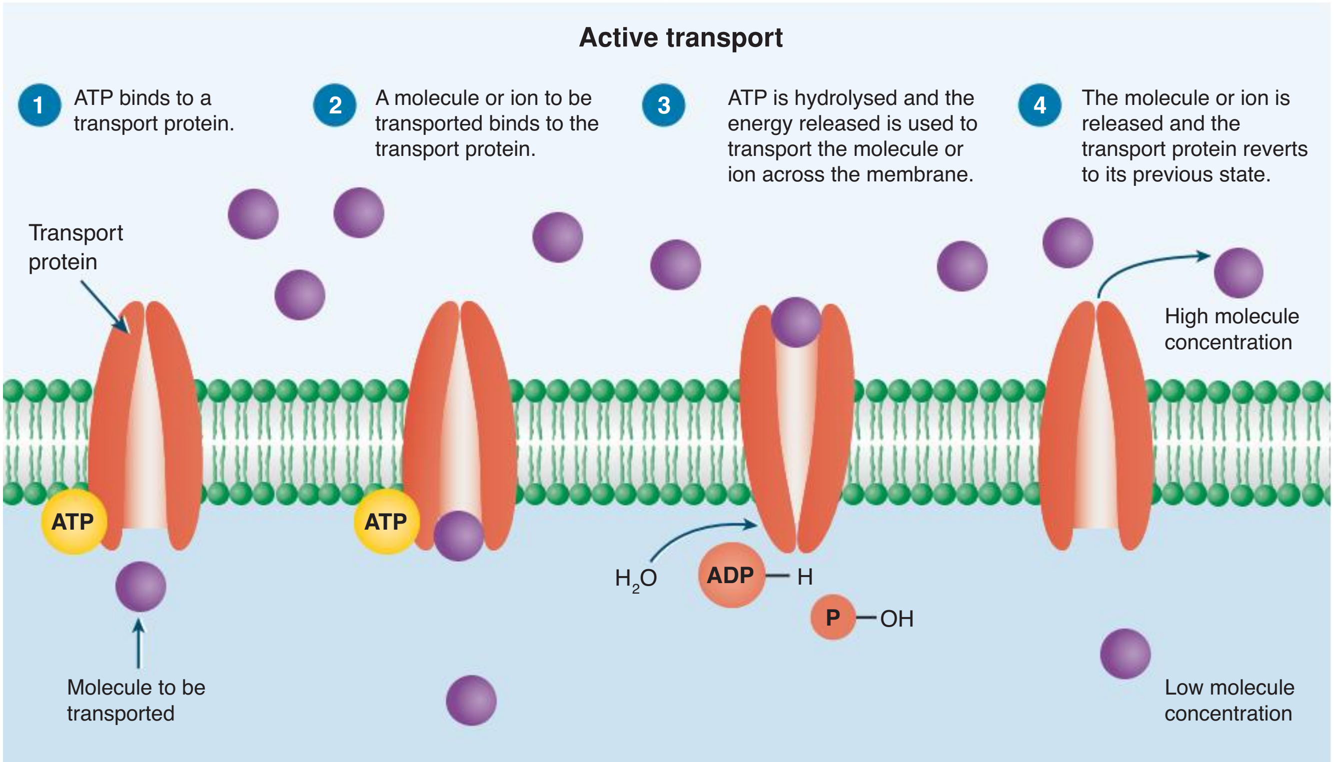
A ball falling is a passive process (it requires no energy input). Replacing the ball requires active energy input.



It requires energy to actively move an object across a physical barrier.



Sometimes the energy of a passively moving object can be used to actively move another. For example, a falling ball can be used to catapult another (left).



1. What is active transport? ____

____

____

2. Where does the energy for active transport come from? ____________________

3. What is the difference between primary active transport and secondary active transport? ________________

____

____

____

____

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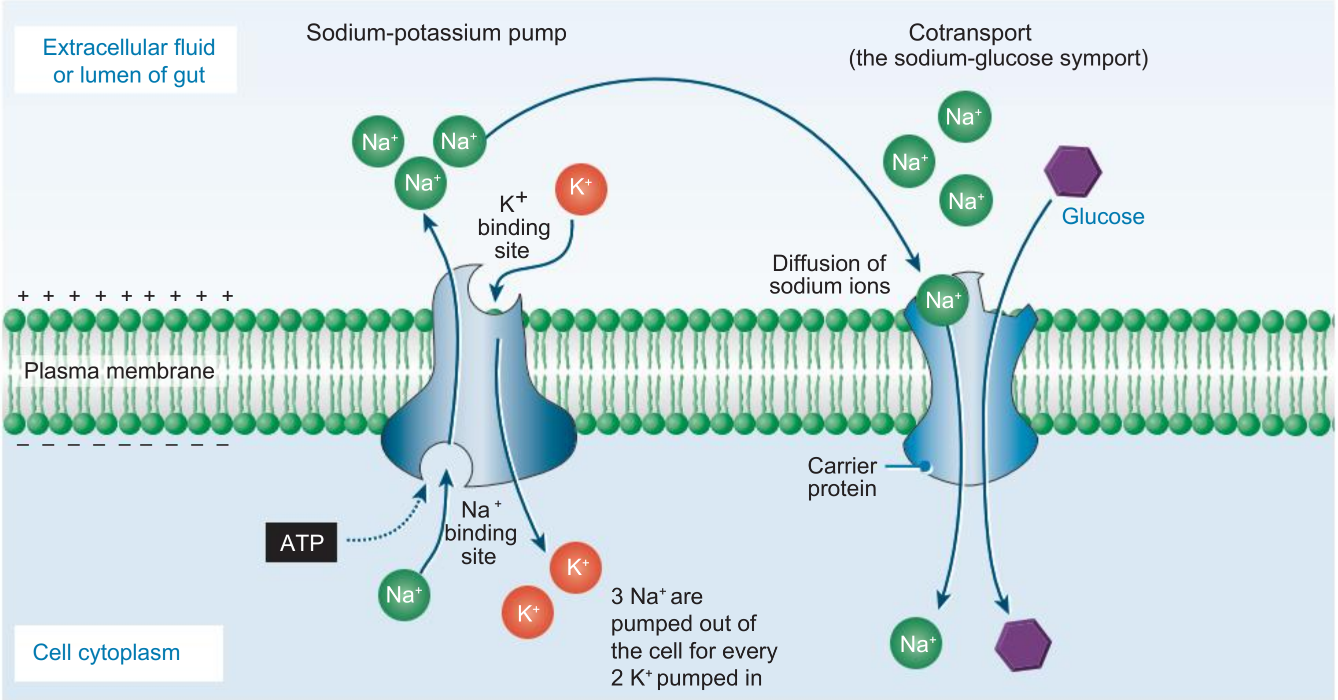
37 Ion Pumps and Cotransport

Key Idea: Ion pumps are transmembrane proteins that use energy to move ions and molecules across a membrane against their concentration gradient.

Sometimes molecules or ions are needed in concentrations that diffusion alone cannot supply to the cell, or they cannot diffuse across the plasma membrane. In this case ion pumps move ions (and some molecules) across the plasma membrane. Proton pumps move H^+ against a concentration gradient to create a potential difference across the membrane that can be used to do work. The sodium-potassium pump (below left) is found in almost all animal cells and is also common in plant cells. The concentration gradient created by ion pumps is often coupled to the transport of other molecules such as glucose across the membrane (below right).



Sodium-potassium (Na^+/K^+) pump

The Na^+/K^+ pump is a protein in the membrane that uses energy in the form of ATP to exchange sodium ions (Na^+) for potassium ions (K^+) across the membrane. The unequal balance of Na^+ and K^+ across the membrane creates large concentration gradients that can be used to drive transport of other substances (e.g. cotransport of glucose). The Na^+/K^+ pump also helps to maintain the right balance of ions and so helps regulate the cell's water balance.

Cotransport (coupled transport)

A gradient in sodium ions drives the active transport of glucose into intestinal epithelial cells. The specific transport protein couples the return of Na^+ down its concentration gradient to the transport of glucose into the intestinal epithelial cell across the cell membrane in contact with the gut lumen. Glucose diffuses from the epithelial cells across the opposite surface and is transported away in the blood. A low intracellular concentration of Na^+ (and therefore the concentration gradient) is maintained by a sodium-potassium pump.

1. Why is ATP required for membrane pump systems to operate? ______

______

2. (a) Explain what is meant by cotransport: ______

______

(b) How is cotransport used to move glucose into the intestinal epithelial cells? ______

______

______

(c) What happens to the glucose that is transported into the intestinal epithelial cells? ______

______

3. (a) The sodium-potassium pump uses primary/secondary (delete one) active transport.

(b) The sodium-glucose symport uses primary/secondary (delete one) active transport.

(c) Describe one consequence of the extracellular accumulation of sodium ions: ______

______

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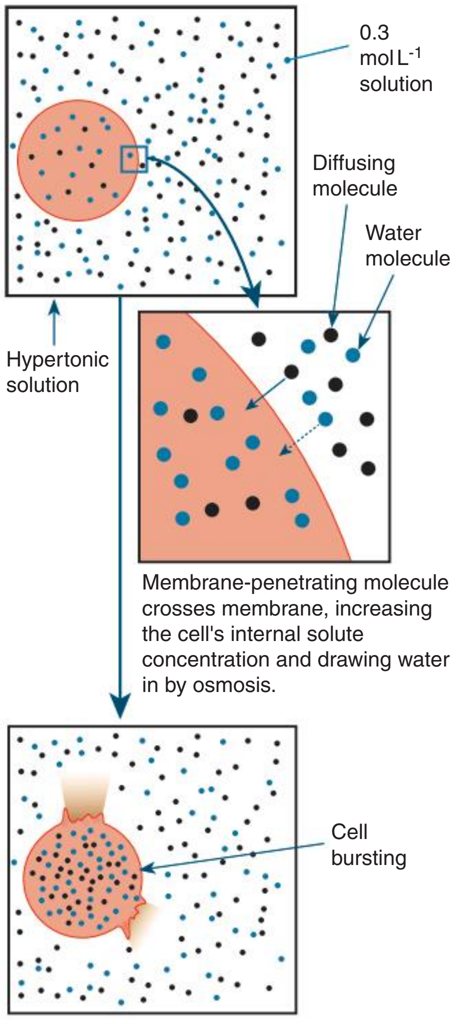
38 Investigating Transport Across Membranes

Key Idea: The rate of diffusion of molecules through the plasma membrane can be determined by measuring the change in light absorbance as a solution of red blood cells haemolyses.

How a cell behaves when suspended in a solution depends on whether or not the molecules or ions in the solution can cross the plasma membrane. If red blood cells (RBCs) are suspended in a concentrated solution of molecules that can readily diffuse across the membrane, the molecules will enter the RBCs by diffusing down their concentration gradient. This will draw water into the RBCs (by osmosis) and they will burst (haemolyse). When the RBCs burst, the cellular material settles out of suspension and the solution becomes clear. By using a spectrophotometer to measure the rate at which the solution becomes clear, it is possible to determine the rate at which the molecules are crossing the plasma membrane.

The aim

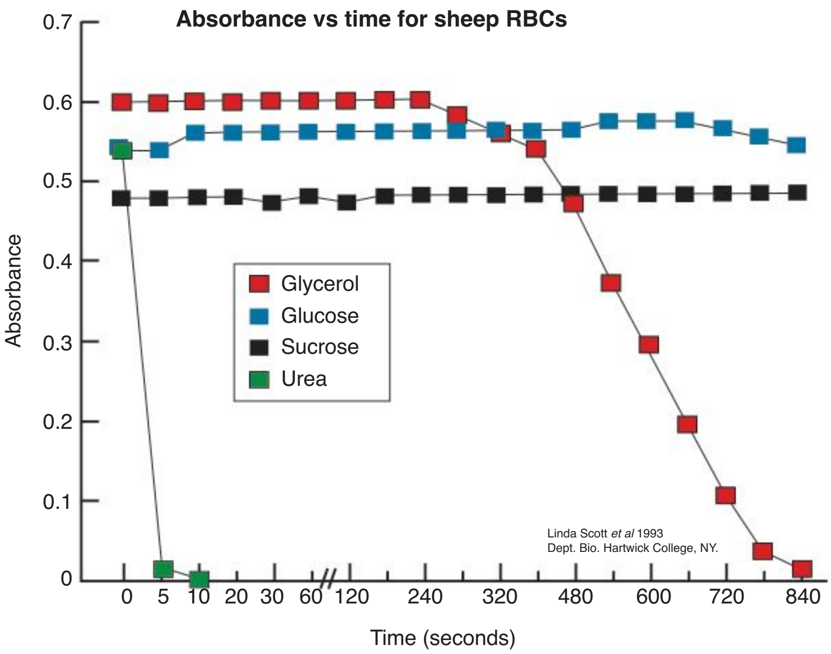
To investigate how the size and membrane solubility of molecules affects the rate of diffusion across the plasma membrane.



Increased cellular volume causes the cell to burst (haemolysis). The cellular material settles out.

The method

- 0.3 mol L^{-1} solutions of glucose, sucrose, urea, and glycerol were prepared (this concentration is greater than the cell internal concentration). A blank solution of distilled water was also prepared. Molecular weights (MW) are as follows: glucose (MW 180), sucrose (MW 342), urea (MW 60), and glycerol (MW 92).
- Both urea and glycerol readily diffuse across the plasma membrane. Glucose is transported across the membrane by a carrier protein.
- 3 mL of each solution was mixed with 0.1 mL of a sheep RBC suspension and added to cuvettes. The cuvettes were placed into a spectrophotometer and absorbance measured over 15 minutes. The results are plotted below:



1. (a) Which molecule crosses the membrane the fastest? ______________________

   (b) Which molecule appears to be unable to cross the plasma membrane? ______________________

   (c) List the molecules in order of their ability to cross the plasma membrane (fastest to slowest):

   ____

2. (a) What is the largest molecule used in the experiment? ______________________

   (b) What is the smallest molecule used in the experiment? ______________________

   (c) How does size affect the rate at which molecules can cross the plasma membrane? ______________________

   ____

3. Why don't the RBCs in the glucose solution haemolyse even though glucose is transported across the membrane?

   ____

   ____

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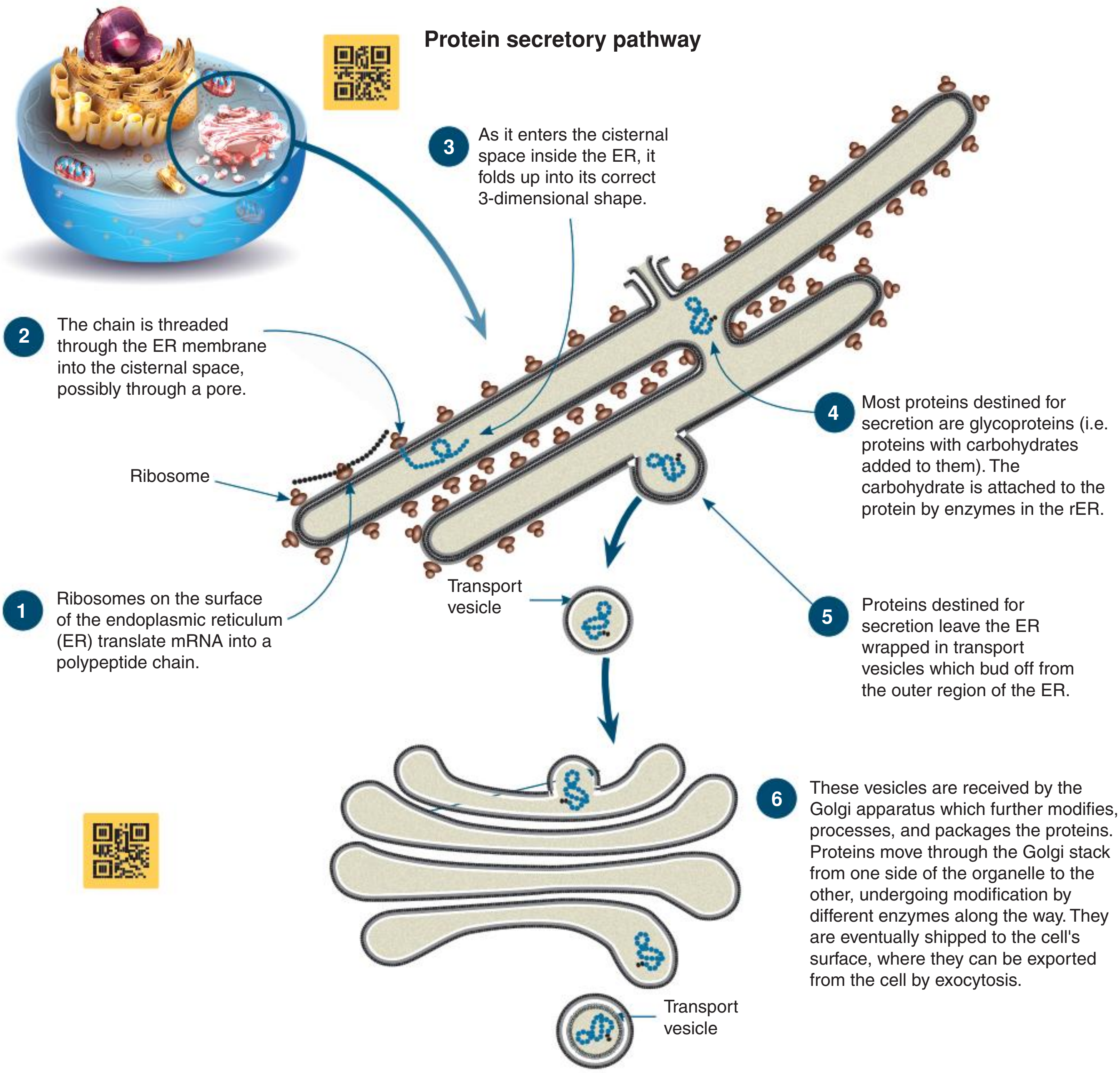
39 Membranes and the Export of Proteins

Key Idea: The synthesis, packaging and movement of macromolecules inside the cell involves coordination between several membrane-bound organelles.

Many proteins need to be modified in order to become functional. This modification takes place in the rough endoplasmic reticulum (rER). From the rER, proteins are transported to the Golgi where the protein is further modified before packaged and shipped to its final destination.

Protein secretory pathway



1. Explain the role of each of the following organelles in the production and transport of proteins:

(a) Ribosomes: ____

____

(b) Endoplasmic reticulum: ____

____

(c) Transport vesicles: ____

____

(d) Golgi apparatus: ____

____

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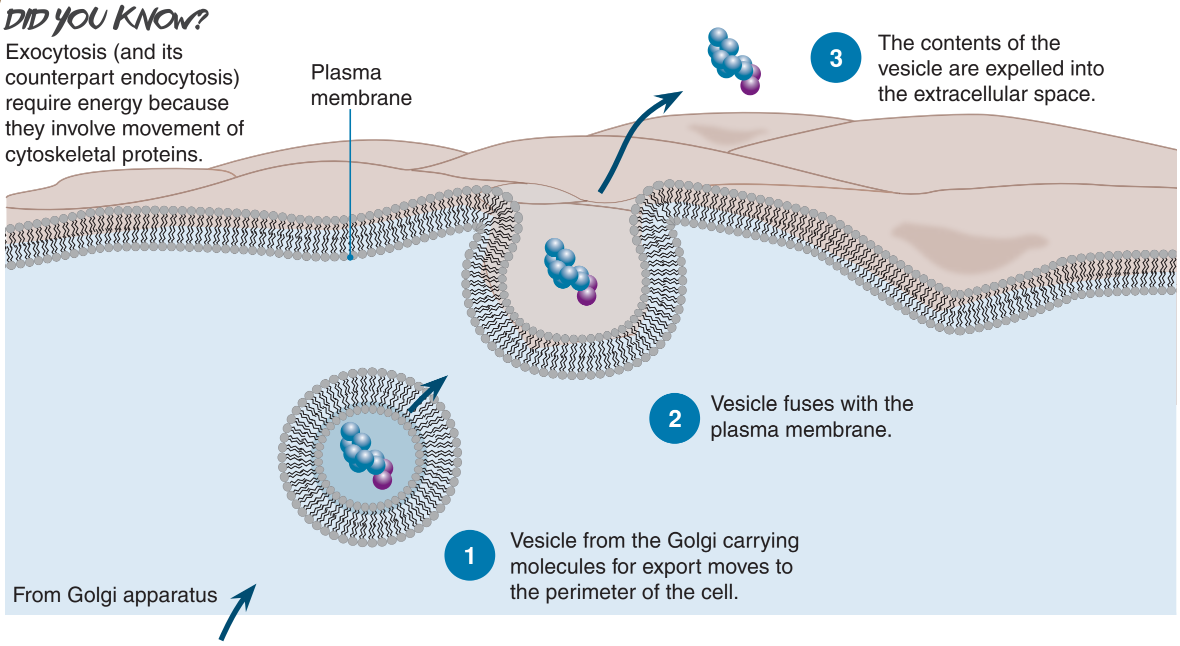
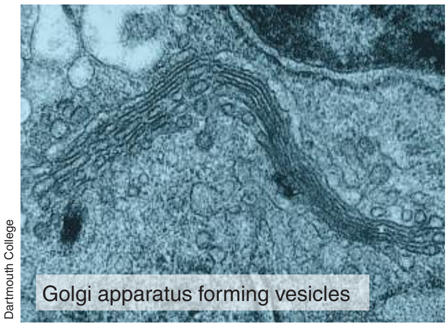
Exocytosis

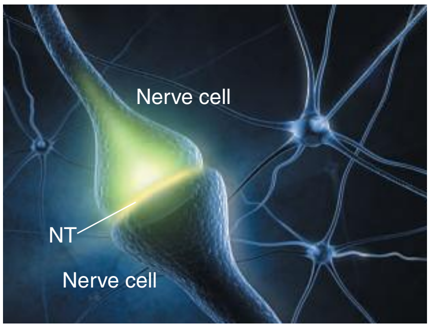
Exocytosis (below) is an active transport process in which a secretory vesicle fuses with the plasma membrane and expels its contents into the extracellular space. In multicellular organisms, various types of cells (e.g. endocrine cells and nerve cells) are specialised to manufacture products, such as proteins, and then export them from the cell to elsewhere in the body or outside it.

DID YOU KNOW?
Exocytosis (and its counterpart endocytosis) require energy because they involve movement of cytoskeletal proteins.

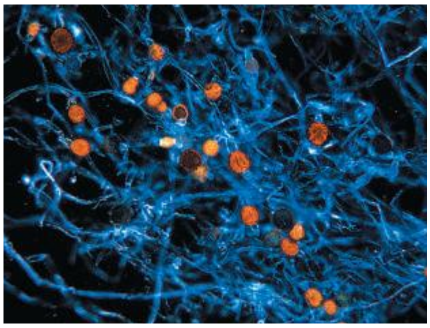




The transport of Golgi vesicles to the edge of the cell and their expulsion from the cell occurs through the activity of the cytoskeleton. This requires energy (ATP).



Exocytosis is important in the transport of neurotransmitters (NT) into the junction (synapse) between nerve cells to transmit nervous signals.



Fungi and bacteria use exocytosis to secrete digestive enzymes, which break down substances extracellularly so that nutrients can be absorbed (by endocytosis).

2. (a) What is the purpose of exocytosis? ____________________

(b) How does it occur? ____________________

3. Describe two examples of the purpose of exocytosis in cells:

(a) ____________________

(b) ____________________

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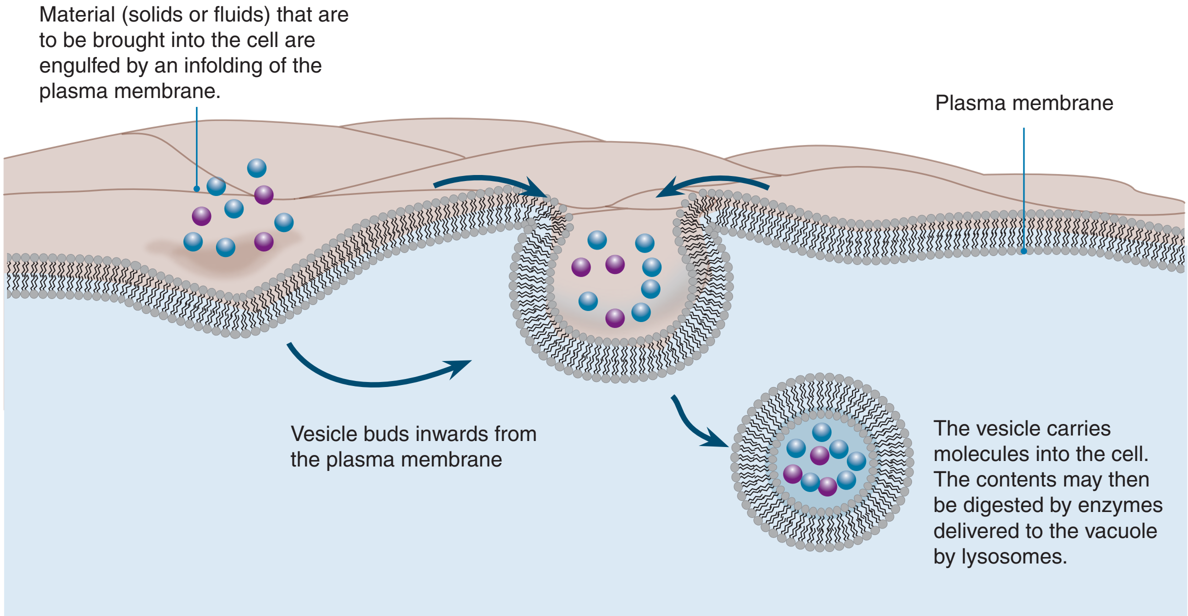
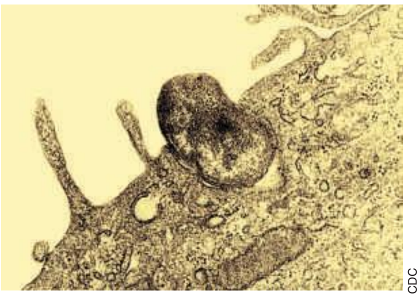
40 Endocytosis

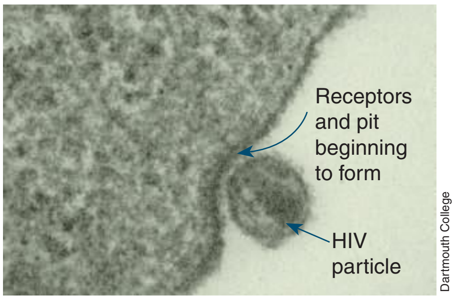
Key Idea: Endocytosis is an active transport process in which the cell engulfs material and draws it in.

Endocytosis is a type of active transport in which the plasma membrane folds around a substance to transport it across the plasma membrane into the cell. The ability of cells to do this is a function of the flexibility of the plasma membrane.

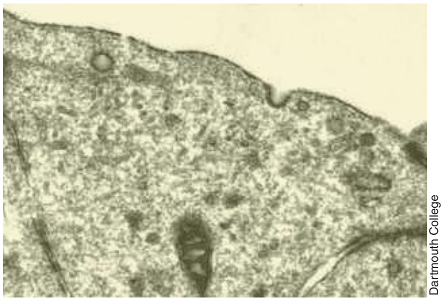




Phagocytosis (or 'cell-eating') involves the cell engulfing solid material to form large phagosomes or vacuoles (e.g. food vacuoles). It may be non-specific or receptor-mediated. Examples: Feeding in *Amoeba*, phagocytosis of foreign material and cell debris by neutrophils and macrophages.



Receptor mediated endocytosis is triggered when certain metabolites, hormones, or viral particles bind to specific receptor proteins on the membrane so that the material can be engulfed. Examples: The uptake of lipoproteins by mammalian cells and endocytosis of viruses (above).



Pinocytosis (or 'cell-drinking') involves the non-specific uptake of liquids or fine suspensions into the cell to form small pinocytic vesicles. Pinocytosis is used primarily for absorbing extracellular fluid. Examples: Uptake in many protozoa, some cells of the liver, and some plant cells.

1. What is the purpose on endocytosis? ______________________

____

2. Is endocytosis active or passive transport? ______________________

3. Describe the following types of endocytosis:

(a) Phagocytosis: ______________________

____

(b) Receptor mediated endocytosis: ______________________

____

(c) Pinocytosis: ______________________

____

4. Explain how the plasma membrane can form a vesicle: ______________________

____

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41 Active and Passive Transport Summary

Key Idea: Cells move materials into and out of the cell by either passive transport, which does not use energy, or by active transport which requires energy, usually as ATP.

The diagram below summarises the movement of material in and out of a cell. Use the information to complete the activity.

A

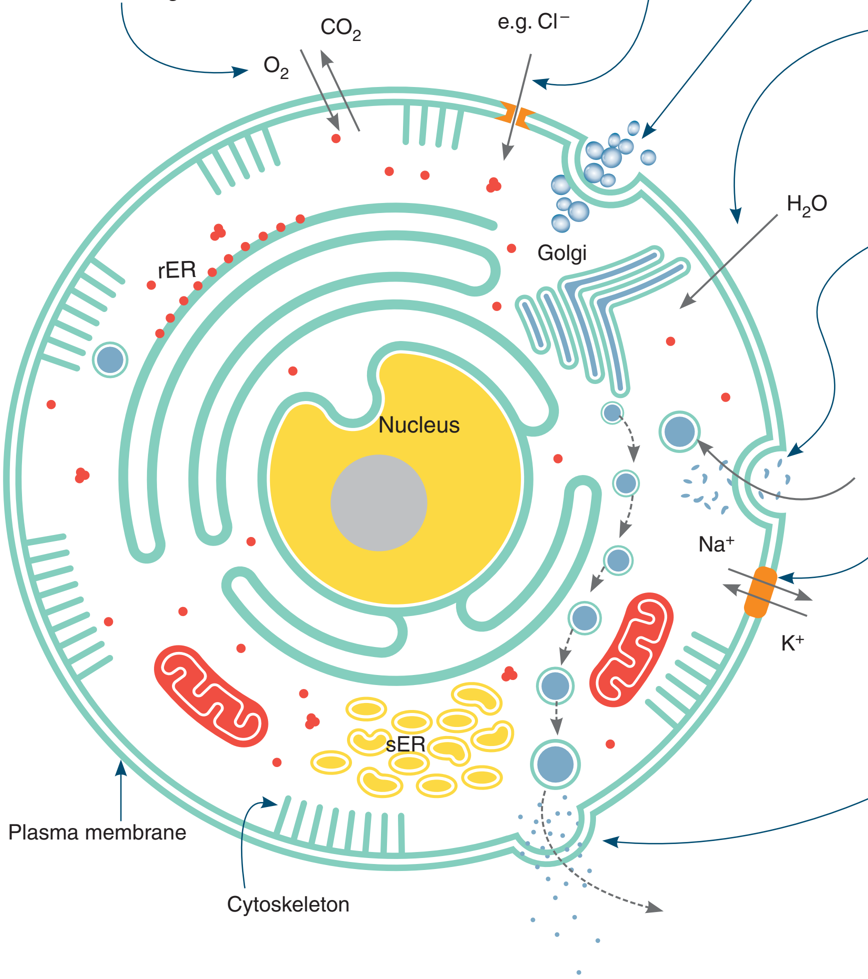
Molecules of liquids, dissolved solids, and gases move into or out of the cell without any expenditure of energy. These molecules move down their own concentration gradients.

B

Diffusion involving a carrier system (channel proteins or carrier proteins) but without any energy expenditure.

C

Fluid or a suspension is taken into the cell. The plasma membrane encloses some of the fluid to form a small vesicle, which then fuses with a lysosome and is broken down.



D

Diffusion of water across a partially permeable membrane. It causes cells in fresh water to take up water.

E

A type of endocytosis in which solids are taken into the cell. The plasma membrane encloses one or more particles and buds off to form a vacuole. Lysosomes fuse with it to digest the contents.

F

A protein in the plasma membrane that uses energy (ATP) to exchange sodium for potassium ions (3 Na^+ out for every 2 K^+ in). The concentration gradient can be used to drive other active transport processes.

G

Vesicles bud off the Golgi or ER and fuse with the plasma membrane to expel their contents into the extracellular fluid.

1. Identify each of the processes (A-G) described in the diagram above in the spaces provided. Indicate whether the transport process is active or passive by using **A** for active and **P** for passive.

2. Identify the transport mechanism involved in each of the following processes in cells:

   (a) Uptake of extracellular fluid by liver cells: ______________________

   (b) Capture and destruction of a bacterial cell by a white blood cell: ______________________

   (c) Movement of water into the cell: ______________________

   (d) Secretion of digestive enzymes from cells of the pancreas: ______________________

   (e) Synthesis of ATP via membrane-bound ATP synthase: ______________________

3. In general terms describe the energy requirements of passive and active transport: ______________________

____

____

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42 KEY TERMS AND IDEAS: Did You Get It?

1. Match each term to its definition, as identified by its preceding letter code.

- active transport ....
- carrier protein ....
- concentration gradient ....
- diffusion ....
- facilitated diffusion ....
- hypertonic ....
- ion pump ....
- osmosis ....
- osmotic potential ....
- passive transport ....
- plasma membrane ....

A A partially permeable phospholipid bilayer forming the boundary of all cells.

B Movement of substances across a biological membrane without energy expenditure.

C The passive movement of molecules from high to low concentration.

D A type of passive transport facilitated by transport proteins.

E A membrane-bound protein involved in the transport of a specific molecule across the membrane either by active transport or facilitated diffusion.

F The energy-requiring movement of substances across a biological membrane against a concentration gradient.

G The tendency of water molecules to move into a solution.

H A transmembrane protein that moves ions across a plasma membrane against their concentration gradient.

I Passive movement of water molecules across a partially permeable membrane down a concentration gradient.

J The gradual difference in the concentration of solutes in a solution between two regions. In biology, this usually results from unequal distribution of ions across a membrane.

K Having a greater concentration of solutes relative to another solution.

2. Explain how the properties of the phospholipid molecule result in the bilayer structure of membranes:

____

____

____

3. Using the formulae: cuboid SA = 2(lh + lw + hw), cuboid volume = lwh, calculate the surface area to volume ratio of the following cell shapes:

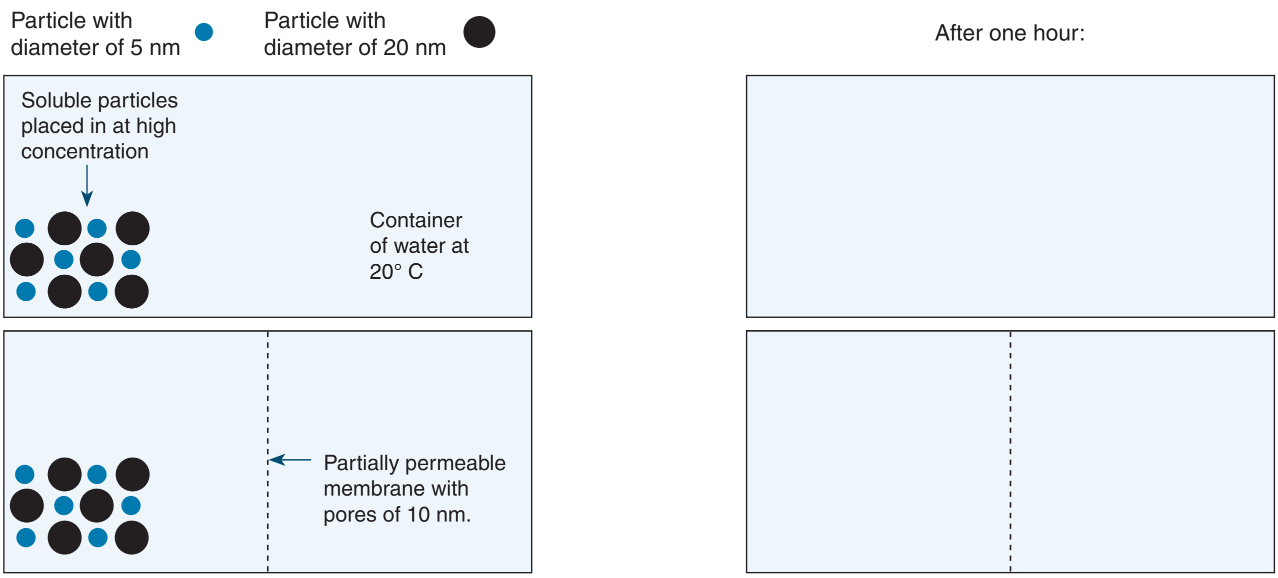
(a) A cubic cell 6 µm x 6 µm x 6 µm: ______________________________

(b) A cuboid cell 1 µm x 12 µm x 5 µm: ______________________________

(c) Which of these cells would exchange substances with its environment most efficiently and why: ______________

____

4. Consider the two diagrams below. For each, draw in the appropriate box what you would expect to see after one hour.



ISBN: 978-1-927309-83-4

UNIT 1
Topic 1

Prokaryotic and Eukaryotic Cells

Key terms

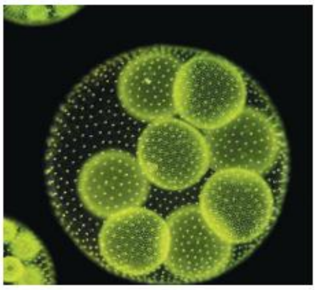
biological molecule
cell wall
centrioles
chloroplast
cilia
cytoplasm
electron micrograph
electron microscope
endoplasmic reticulum (ER)
eukaryotic cell
flagella
Golgi
light (=optical) microscope
lysosome
magnification
mitochondrion
nucleolus
nucleus
organelles
pigment
plasma membrane
prokaryotic cell
resolution
ribosome
rough ER (rER)
smooth ER (sER)
stain
vacuole

Activity number

Cells are the unit of life

Key skills and knowledge

- ☐ 1 Recognise cells as the basic unit of life on Earth and outline the basic principles of the cell theory. **43**
- ☐ 2 **SHE** Link the history of the cell theory to the development of microscopes. **43**
- ☐ 3 Recognise the requirements of all cells for survival, including sources of energy, gases, and nutrients, and removal of wastes. **44 45**
- ☐ 4 Recognise the features that prokaryotic and eukaryotic cells have in common. Explain how these commonalities are the result of their shared ancestry. **46 47**
- ☐ 5 Describe the range of cell sizes. Express cell sizes in different units of measurement (mm, µm, nm). **48**
- ☐ 6 Recall the distinguishing features of prokaryotic cells, including small size (relative to eukaryotic cells), lack of a nucleus and membrane-bound organelles, and the presence of a single, circular chromosome. Prokaryotes usually exist as single cells but may be colonial, with some specialisation of function. **46**



Eukaryotic cells have specialised organelles

Key skills and knowledge

- ☐ 7 Understand that eukaryotic cells have specialised organelles and describe the role of these in the functioning of the cell and the organism, including: **49 51**
  - chloroplasts and plastids other than chloroplasts
  - mitochondria
  - rough and smooth endoplasmic reticulum (rER and sER)
  - Golgi
  - lysosomes
- ☐ 8 Identify which of the above organelles are present in plant cells, animal cells, or both plant and animal cells. **49 51**
- ☐ 9 Identify chloroplasts, mitochondria, rough endoplasmic reticulum, and lysosomes in electron micrographs. **50 52**
- ☐ 10 Use drawings and electron micrographs to compare and contrast the structure of prokaryotic cells and eukaryotic cells. **46 50 52 54**

Studying eukaryotic cells

Key skills and knowledge

- ☐ 11 Understand the structure and basic principles of light (optical) microscopes. Contrast light and electron microscopy in terms of magnification and resolution. **55**
- ☐ 12 **SKILL** Construct a wet mount for viewing with a light microscope. Use a light microscope to locate prepared material and focus images. **55 56 57**
- ☐ 13 **PRAC** Prepare wet mounts and use a light microscope to observe cells and identify structures and organelles in microorganisms, plants, and animals (cytoplasm, cell wall, cell membrane, chloroplasts, nucleus). Calculate magnification and field of view. **53-59**
- ☐ 14 **PRAC** Use electron micrographs to identify organelles in cells. **50 52**

43 The Cell is the Unit of Life

Key Idea: All living organisms are composed of cells. Cells are broadly classified as prokaryotic or eukaryotic.

The cell theory is a fundamental idea of biology. This idea, that all living things are composed of cells, developed over many years and is strongly linked to the invention and refinement of the microscope in the 1600s.

The cell theory

The idea that cells are fundamental units of life is part of the cell theory. The basic principles of the theory are:

- All living things are composed of cells and cell products.
- New cells are formed only by the division of pre-existing cells.
- The cell contains inherited information (genes) that are used as instructions for growth, functioning, and development.
- The cell is the functioning unit of life; all chemical reactions of life take place within cells.

All cells show the functions of life

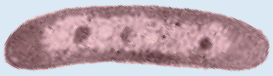
Cells use food (e.g. glucose) to maintain a stable internal environment, grow, reproduce, and produce wastes. The sum total of all the chemical reactions that sustain life is called metabolism.

Movement
Respiration
Sensitivity
Growth
Reproduction
Excretion
Nutrition

Living things

Cells

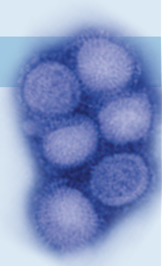
Prokaryotic (bacterial) cells



- Autotrophic or heterotrophic
- Single celled
- Lack a membrane-bound nucleus and membrane-bound organelles
- Cells 0.5-10 µm
- DNA a single, circular chromosome. There may be small accessory chromosomes called plasmids.
- Cell walls containing peptidoglycan.

Viruses are non-cellular

- Non-cellular.
- Typical size range: 20-300 nm.
- Contain no cytoplasm or organelles.
- No chromosome, just RNA or DNA strands.
- Enclosed in a protein coat.
- Depend on cells for metabolism and reproduction (replication).



CDC

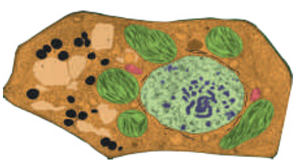
Influenzavirus

Eukaryotic cells

- Cells 30-150 µm
- Membrane-bound nucleus and membrane-bound organelles
- Linear chromosomes

Plant cells

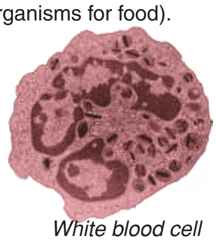
- Exist as part of multicellular organism with specialisation of cells into many types.
- Autotrophic (make their own food): photosynthetic cells with chloroplasts.
- Cell walls of cellulose.



Generalised plant cell

Animal cells

- Exist as part of multicellular organism with specialisation of cells into many types.
- Lack cell walls.
- Heterotrophic (rely on other organisms for food).



White blood cell

Protist cells

- Mainly single-celled or exist as cell colonies.
- Some are autotrophic and carry out photosynthesis.
- Some are heterotrophic.

Amoeba cell

Fungal cells

- Rarely exist as discrete cells, except for some unicellular forms (e.g. yeasts)
- Plant-like, but lack chlorophyll.
- Rigid cell walls containing chitin.
- Heterotrophic.

Yeast cell

1. What are the characteristic features of a prokaryotic cell? ______________________________

____

2. What are the characteristic features of a eukaryotic cell? ______________________________

____

3. Why are viruses considered to be non-cellular (non-living)? ______________________________

____

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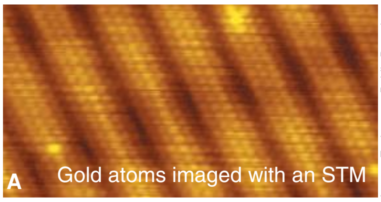
SHE

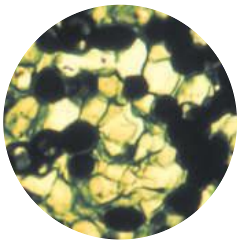
Microscopes have been used for hundreds of years. Advances in microscopy and in electronic and computer technology have helped us visualise ever smaller objects, right down to the scale of the atom.

Gerd Binning and **Heinrich Rohrer** invent the scanning tunneling electron microscope (STM), which produces 3D images to the atomic level



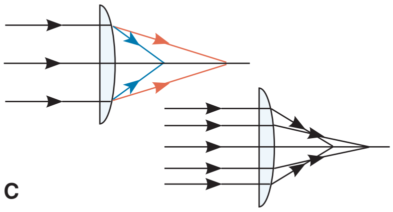
A Gold atoms imaged with an STM

Robert Hooke of England uses the term 'cell' in describing the microscopic structure of cork.



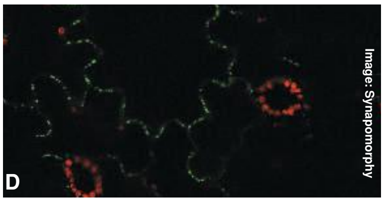
B

Discoveries reducing the effect of chromatic aberration (top) and spherical aberration (bottom) allow microscopes to produce clearer images.



C

Marvin Minsky patents the principle of the confocal laser scanning microscope (CLSM) but it takes 30 years for development.



D

Albert von Kolliker describes mitochondria.

E

Hugo von Mohl describes chloroplasts in plant cells.

F

Antoni van Leeuwenhoek's microscope was only a glorified magnifying glass by today's standards but he used it to discover protozoa and bacteria.

G

Matthias Jakob Schleiden and **Theodor Schwann** propose that all tissues are composed of cells and that cell are the basic building blocks of life.

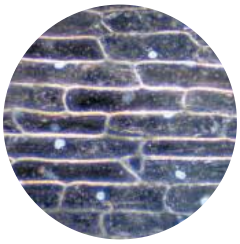
H

Robert Brown discovers the nucleus in plant cells.

I

Frits Zernike invents the phase-contrast microscope making transparent or colourless objects easier to view.

Onion cells viewed by phase contrast.

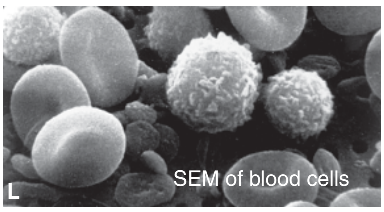


J

Zacharias Janssen of Holland has been credited with the first compound microscope (more than one lens).

K

Manfred von Ardenne develops the scanning electron microscope (SEM) allowing the surface of objects to be imaged.


L SEM of blood cells

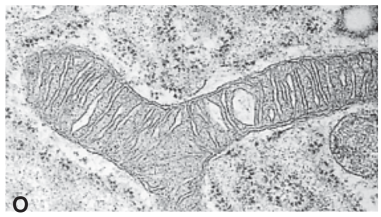
Rudolf Virchow concludes that all cells develop from existing cells.

M

Camillo Golgi describes the Golgi apparatus.

N

Ernst Ruska develops the transmission electron microscope (TEM) allowing the interior of cells to be viewed with high clarity. Image: TEM of mitochondrion.



O

4. (a) Research the above milestones in cell theory and microscopy to place them in the correct chronological order, including their year:

____

____

(b) How have advances in microscopy helped advance our knowledge of cells? ______________________

____

____

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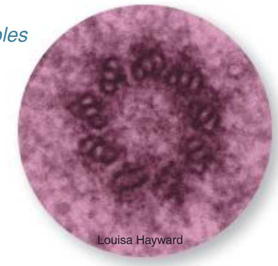
44 What Are Cells Made Of?

Key Idea: The main components of a cell are water and compounds of carbon, hydrogen, nitrogen, and oxygen.

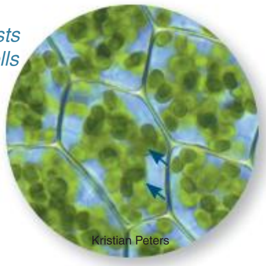
Water is the main component of cells and organisms, providing an aqueous environment in which metabolic reactions can occur. Apart from water, most other substances in cells are compounds of carbon, hydrogen, oxygen, and nitrogen. Carbon can combine with many other elements to form a large number of carbon-based (or organic) molecules. The organic molecules that make up living things can be grouped into four broad classes: carbohydrates, lipids, proteins, and nucleic acids. In addition, a small number of inorganic ions are also components of larger molecules.

Centrioles



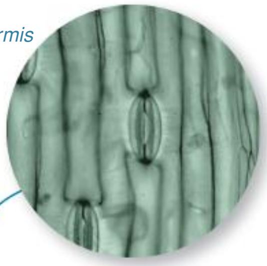
Proteins have an enormous number of structural and functional roles in plants and animals, e.g. as enzymes, structural materials (such as collagen), in transport, and movement (e.g. cytoskeleton and centrioles).

Chloroplasts in plant cells



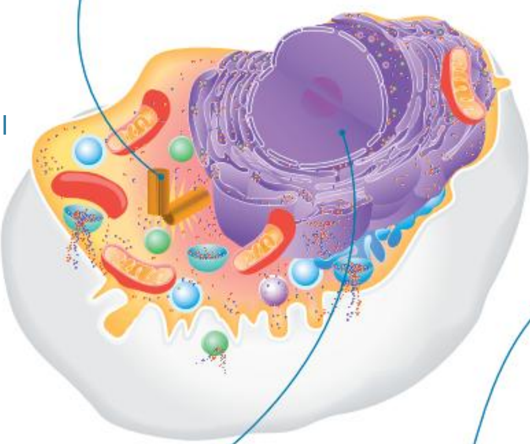
Inorganic ions: Dissolved ions participate in metabolic reactions and are components of larger organic molecules, e.g. Mg^{2+} is a component of the green chlorophyll pigment in the chloroplasts of green plants.

Plant epidermis

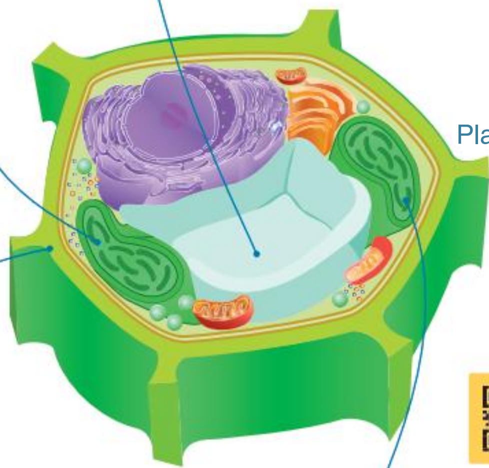


Water is a major component of cells: many substances dissolve in it and metabolic reactions occur in it. In plant cells, fluid pressure against the cell wall provides turgor, which supports the cell.

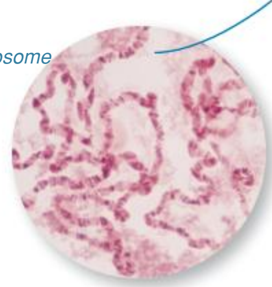
Animal cell



Plant cell

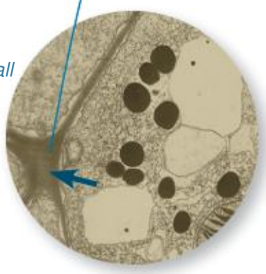


Chromosome



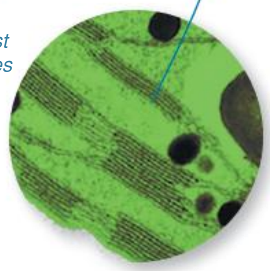
Nucleotides and nucleic acids
Nucleic acids encode information for the construction and functioning of an organism (DNA and RNA). ATP, a nucleotide derivative, is the energy carrier of the cell.

Plant cell wall



Carbohydrates form the structural components of cells, e.g. cellulose cell walls (arrowed). They are important in energy storage and they are involved in cellular recognition.

Chloroplast membranes



Lipids provide a concentrated source of energy. Phospholipids are a major component of cellular membranes, including the membranes of organelles such as chloroplasts and mitochondria.

1. Given the components of cells above, predict some substances they need to remain functioning and the importance of those substance:

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45 What Cells Need for Survival

Key Idea: Cells have specific requirements for survival. These include obtaining nutrients and removing wastes.

Cells require energy to power the reactions that build their structures and maintain their functions. Cells also require a range of molecules and ions to build and maintain these structures and they need to be able to remove wastes.

Cells need energy

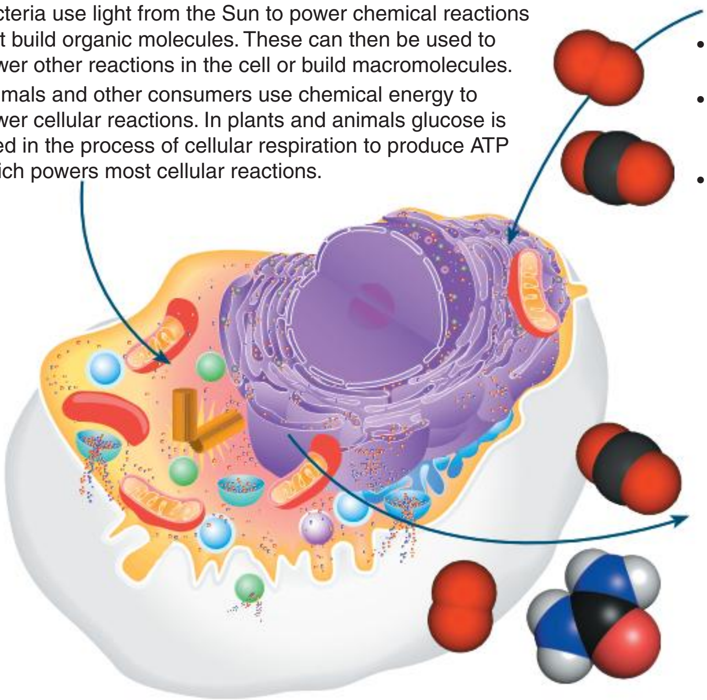
Cells have evolved to use two basic forms of energy: light or chemical energy.

- Plant and algal cells containing chloroplasts and some bacteria use light from the Sun to power chemical reactions that build organic molecules. These can then be used to power other reactions in the cell or build macromolecules.
- Animals and other consumers use chemical energy to power cellular reactions. In plants and animals glucose is used in the process of cellular respiration to produce ATP which powers most cellular reactions.

Cells require resources

Cells require molecules and ions to build macromolecules and help carry out cellular reactions.

- Carbon dioxide is needed by plants to build organic molecules during photosynthesis.
- Oxygen is needed by plants and animals as an electron acceptor at the end of cellular respiration.
- In plants, nitrates provide nitrogen, which is incorporated into amino acid molecules. Animals use these (by eating plants or plant eaters) to obtain building blocks for their proteins.
- Various metal ions are also needed. Some in relatively large amounts, e.g. Na^+ is needed for nerve cell function in animals, while others are needed only in very small amounts.



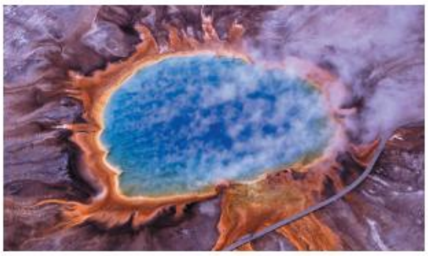
Cells need to remove wastes

Cells need to remove wastes generated during cellular reactions. What is regarded as a waste depends on the type of cell.

- Oxygen is a waste product of photosynthesis, but is required for cellular respiration.
- Other waste products include nitrogen wastes such as urea, ammonia, and uric acid (from metabolic processes).
- Most cellular reactions generate heat, which must be managed so that an organism does not overheat. In animals, metabolic heat is removed from cells by the blood and transferred to places where it can radiate into the environment (e.g. the skin).

Cellular environments

The exact conditions a cell needs depends on many factors including whether the organism is unicellular or multicellular, and what environment it has evolved to survive in.



Jim Peaco, National Park Service PD

Some unicellular organisms (called thermophiles) can survive in temperatures as high as 122°C. Their enzymes can not function at the low temperatures experienced outside environments such as hot thermal pools.

Halophiles require environments with high salt concentrations (up to five times as concentrated as the sea). These cells are specially adapted to retain water. If placed in fresh water they quickly swell and burst.

Cells in multicellular organisms require the homeostatic environment provided by the organism. The organism provides an internal environment that provides the cells with nutrients, waste removal, and a relatively constant temperature.

1. Why do cells need energy? ______________________________

____

2. Why must cells be able to remove wastes? ______________________________

____

3. Describe an example of where waste products of one cellular process can be used as a resource for another:

____

____

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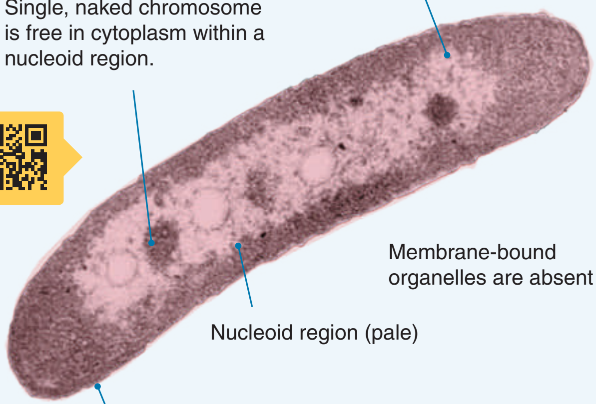
46 Prokaryotic vs Eukaryotic Cells

Key Idea: Cells are classified as either prokaryotic or eukaryotic and are distinguished on the basis of their size, internal organisation, and complexity.

Cells are divided into two broad groups based on their size and organisation. Prokaryotic cells (all Bacteria and Archaea) are small, single cells with a simple internal structure. Eukaryotic cells are larger, more complex cells. All multicellular and some unicellular organisms are eukaryotic.

Prokaryotic cells

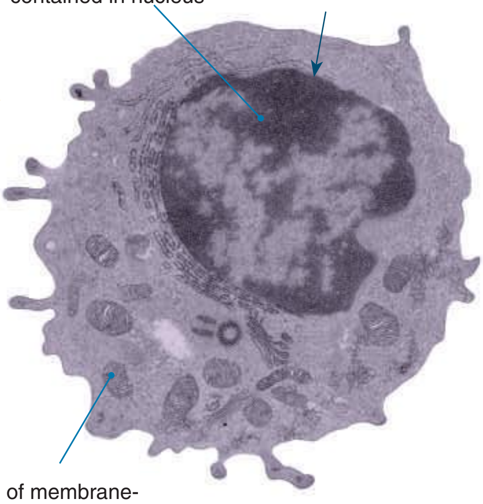
- Prokaryotic cells lack a membrane-bound nucleus or any membrane-bound organelles.
- Prokaryotic cells are often also called bacterial cells. Examples of bacterial cells include *E. coli* and *Staphylococcus aureus*.
- They are small (generally 0.5-10 µm) single cells (unicellular).
- They are relatively unstructured and have little cellular organisation (their DNA, ribosomes, and enzymes are free floating within the cell cytoplasm).
- Single, circular chromosome of naked DNA.
- Prokaryotes have cell walls, but it is different to the cell walls that some eukaryotes have.



The image above shows a bacterium called *Escherichia coli*

Eukaryotic cells

- Eukaryotic cells have a membrane-bound nucleus, and other membrane-bound organelles.
- Plant cells, animal cells, fungal cells, and protists are all eukaryotic cells.
- Eukaryotic cells are large (30-150 µm). They may exist as single cells or as part of a multicellular organism.
- Multiple linear chromosomes consisting of DNA and associated proteins.
- They are more complex than prokaryotic cells, with more structure and internal organisation.



A human white blood cell (above) is an example of an animal cell

1. List three features of a prokaryotic cell:

   (a) ______________________________

   (b) ______________________________

   (c) ______________________________

   (d) Name an example of a prokaryote: ______________________________

2. List three features of a eukaryotic cell:

   (a) ______________________________

   (b) ______________________________

   (c) ______________________________

   (d) Name examples of eukaryotic cells: ______________________________

   ____

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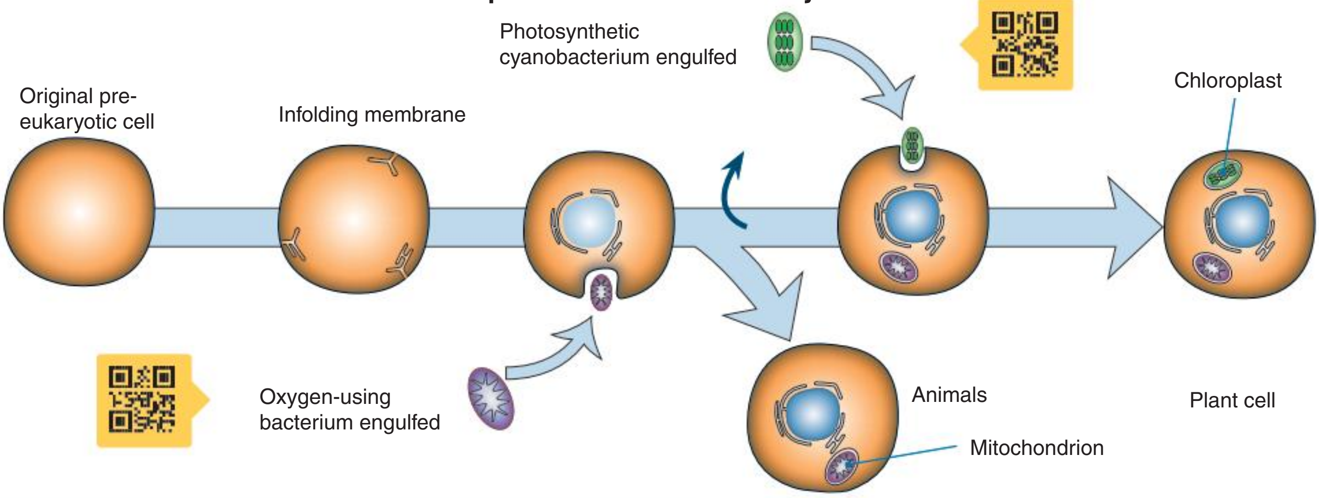
47 Origins of Eukaryotes

Key Idea: Eukaryotes probably formed when a small prokaryote-like cell was engulfed by a larger one and formed an endosymbiotic relationship.

The first eukaryotes were unicellular and occur only rarely in microfossils. The first fossil evidence dates to 2.1 bya, but molecular evidence suggests that the eukaryotic lineage is much more ancient and closer to the origin of life. The original endosymbiotic theory (Margulis, 1970) proposed that eukaryotes arose as a result of an endosymbiosis between two prokaryotes, one of which was aerobic and gave rise to the mitochondrion. The hypothesis has since been modified to recognise that eukaryotes probably originated with the appearance of the nucleus and flagella, and later acquired mitochondria and chloroplasts by endosymbiosis. Primitive eukaryotes probably acquired mitochondria by engulfing purple bacteria. Similarly, chloroplasts may have been acquired by engulfing primitive cyanobacteria. In both instances, the organelles produced then became dependent on the nucleus of the host cell to direct some of their metabolic processes.

Proposed evolution of eukaryotes

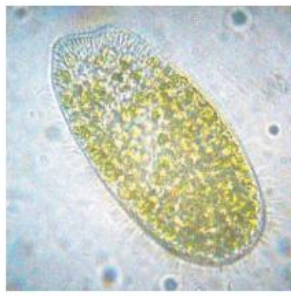


Evidence for the bacterial origin of chloroplasts and mitochondria

- Chloroplasts and mitochondria divide by binary fission, they split in half to form new copies of themselves, just like bacteria. Thus new chloroplasts and mitochondria arise from preexisting chloroplasts and mitochondria, they are not manufactured by the cell.
- They have a chemically distinct inner membrane. The outer membrane is similar to the plasma membrane (as if a vesicle formed around the engulfed bacteria) but the inner membrane is similar to the membrane of bacteria.
- Bacterial DNA is a single circular molecule. Mitochondria and chloroplasts also have their own single, circular DNA. Like bacterial DNA, the DNA of mitochondria and chloroplasts has no introns or histones and mutates at a different rate to the nuclear DNA.
- Chloroplasts and mitochondria contain ribosomes that are more similar in size to bacterial ribosomes.
- Antibiotics that inhibit protein synthesis in bacteria also inhibit protein synthesis in mitochondria and chloroplasts.
- Analysis of chloroplast DNA has shown that they are related to cyanobacteria.

Examples of engulfment

Paramecium bursaria



Paramecium bursaria (right) is a single celled protozoan. It engulfs cells of *Zoochlorella*, a photosynthetic green alga. It houses the algae and carries them to light areas in a pond where they can photosynthesise. In return, it uses the food made by the algae.

Amoeba proteus

From 1972 microbiologist Kwang Jeon studied the infection of *Amoeba proteus* by *Legionella*-like bacteria. He found that most infected amoebae died. The few that survived were cultured over many generations. Eventually, the amoebae became dependent on the bacteria for nuclear function. Experiments showed that when the nucleus of an infected cell was placed in an uninfected cell which had also had its nucleus removed the new cell quickly died.

1. Outline three pieces of evidence for the bacterial origin of chloroplasts and mitochondria:

   (a) ______________________________

   (b) ______________________________

   (c) ______________________________

2. How do the examples of *Paramecium bursaria* and *Amoeba proteus* support the endosymbiotic origin of chloroplasts?

____

____

____

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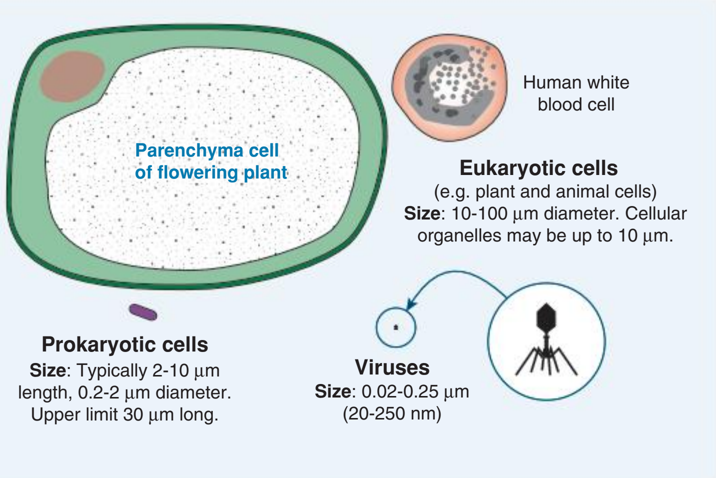
48 Cell Sizes

Key Idea: Cells vary in size (2-100 µm), with prokaryotic cells being approximately 10 times smaller than eukaryotic cells.

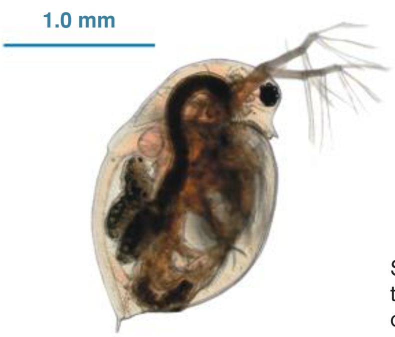
Cells can only be seen properly when viewed through the magnifying lenses of a microscope. The images below show a variety of cell types, including a multicellular microscopic animal and a virus (non-cellular) for comparison. For each of these images, note the scale and relate this to the type of microscopy used.



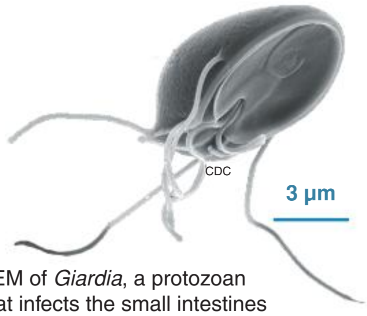
Unit of length (international system)

Unit	Metres	Equivalent
1 metre (m)	1 m	= 1000 millimetres
1 millimetre (mm)	10^{-3} m	= 1000 micrometres
1 micrometre (µm)	10^{-6} m	= 1000 nanometres
1 nanometre (nm)	10^{-9} m	= 1000 picometres

Micrometres are sometime referred to as microns. Smaller structures are usually measured in nanometres (nm) e.g. molecules (1 nm) and plasma membrane thickness (10 nm).

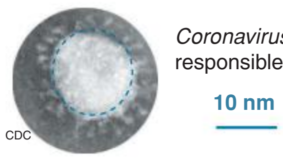


Daphnia is a small crustacean found as part of the zooplankton of lakes and ponds.



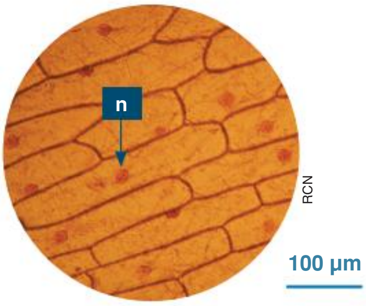
SEM of *Giardia*, a protozoan that infects the small intestines of many vertebrate groups.

Paramecium is a protozoan commonly found in ponds.

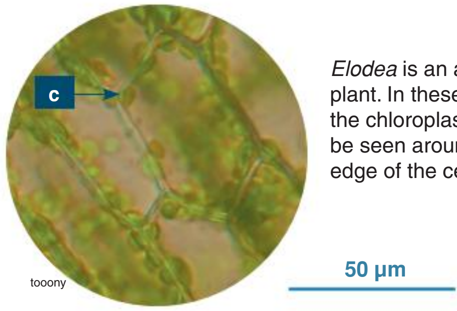


Coronavirus is the virus responsible for SARS.

Salmonella is a bacterium found in many environments and causes food poisoning in humans.



Onion epidermal cells: the nucleus (n) is just visible.



Elodea is an aquatic plant. In these leaf cells, the chloroplasts (c) can be seen around the inner edge of the cells.

1. Using the measurement scales provided on each of the photographs above, determine the longest dimension (length or diameter) of the cell/animal/organelle indicated in µm and mm. Attach your working:

(a) *Daphnia*: ____________ µm ____________ mm

(b) *Giardia*: ____________ µm ____________ mm

(c) Nucleus ____________ µm ____________ mm

(d) *Elodea* leaf cell: ______ µm ____________ mm

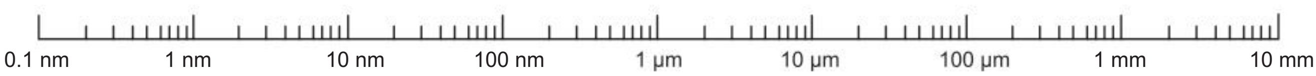
(e) Chloroplast: ____________ µm ______________ mm

(f) *Paramecium*: ____________ µm ______________ mm

(g) *Salmonella*: ____________ µm ______________ mm

(h) *Coronavirus*: ____________ µm ______________ mm

2. Mark and label the examples above on the log scale below according to their size:



ISBN: 978-1-927309-83-4

49 Plant Cells

Key Idea: Plant cells are eukaryotic cells. They have features in common with animal cells, but also several unique features.

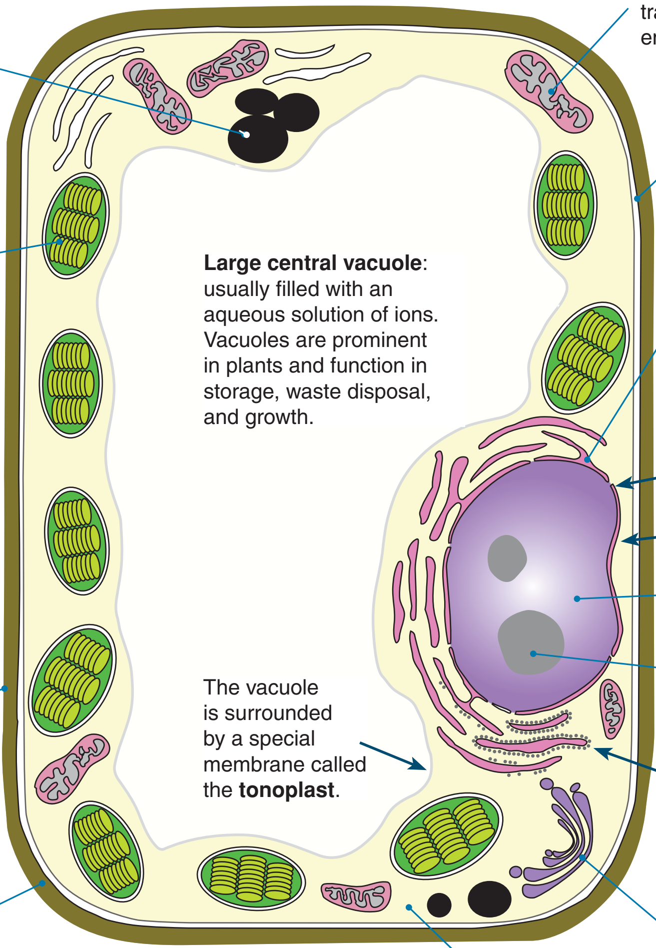
Eukaryotic cells have a similar basic structure, although they may vary tremendously in size, shape, and function. Certain features are common to almost all eukaryotic cells, including their three main regions: a nucleus, surrounded by a watery cytoplasm, which is itself enclosed by the plasma membrane. Plant cells are enclosed in a cellulose cell wall, which gives them a regular, uniform appearance. The cell wall protects the cell, maintains its shape, and prevents excessive water uptake. It provides rigidity to plant structures but permits the free passage of materials into and out of the cell.

Generalised plant cell

Starch granule: Carbohydrate stored in **amyloplasts** (specialised storage organelles).

Chloroplast: Specialised organelles, 2 µm x 5 µm, containing the green pigment chlorophyll. Chloroplasts contain dense stacks of membranes within a fluid which is much like cytosol. They are the sites for photosynthesis and are found mainly in leaves. Chloroplasts are one of a group of double membraned organelles called **plastids**, which include amyloplasts (see above).

Cell wall: A semi-rigid structure outside the plasma membrane, 0.1 µm to several µm thick. It is composed mainly of cellulose. It supports the cell and limits its volume.



Mitochondrion: 1.5 µm X 2–8 µm. They are the cell's energy transformers, converting chemical energy into ATP.

Plasma membrane: Located inside the cell wall in plants, 3 to 10 nm thick.

Endoplasmic reticulum (ER): A network of tubes and flattened sacs. ER is continuous with the nuclear membrane and may be smooth or have attached ribosomes (rough ER).

Nuclear pore: 100 nm diameter

Nuclear membrane: a double layered structure.

Nucleus: A conspicuous organelle 5 µm diameter.

Nucleolus

Ribosomes: These small (20 nm) structures manufacture proteins. They may be free in the cytoplasm or associated with the surface of the endoplasmic reticulum.

Golgi apparatus

Cytoplasm: A watery solution containing dissolved substances, enzymes, and the cell organelles and structures.

Middle lamella (seen here between adjacent cells left): The first layer of the cell wall formed during cell division. It contains pectin and protein, and provides stability. It allows the cells to form **plasmodesmata (P)**, special channels that allow communication and transport to occur between cells.

1. (a) What are the functions of the cell wall in plants? ______________________

____

(b) Why is the middle lamella of the cell wall important? ______________________

____

2. What distinguishes the tonoplast and the plasma membrane? ______________________

____

3. (a) What structure takes up the majority of space in the plant cell? ______________________

(b) What are its roles? ______________________

4. Identify two structures in the diagram that are not found in animal cells: ______________________

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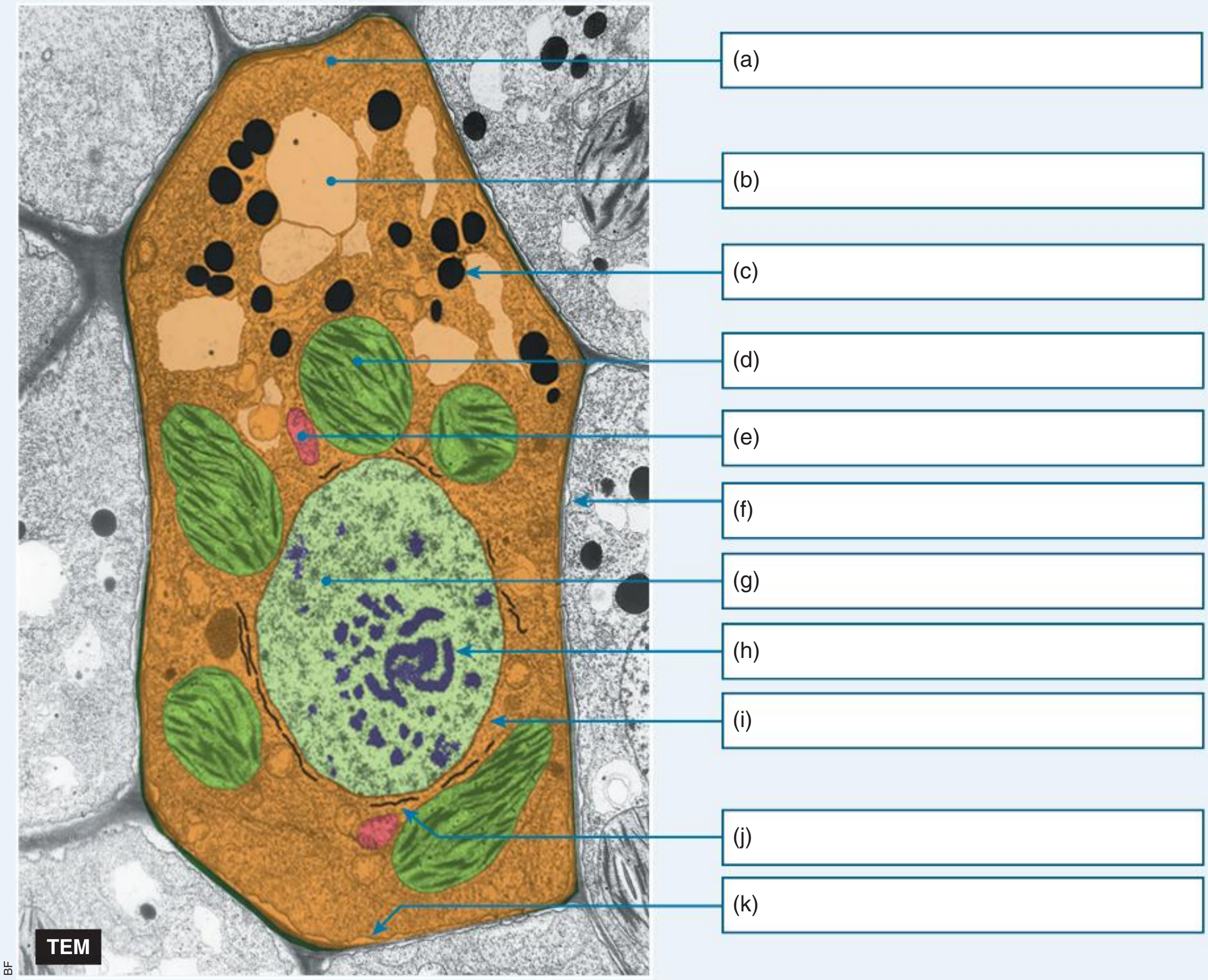
50 Identifying Structures in a Plant Cell

Key Idea: The position and appearance of the organelles in an electron micrograph can be used to identify them.

1. Study the diagrams on the other pages in this chapter to familiarise yourself with the structures found in eukaryotic cells. Identify the 11 structures in the cell below using the following word list: *cytoplasm, smooth endoplasmic reticulum, mitochondrion, starch granule, chromosome, nucleus, vacuole, plasma membrane, cell wall, chloroplast, nuclear membrane*



2. State how many cells, or parts of cells, are visible in the electron micrograph above: ____________________

3. Describe the features that identify this cell as a plant cell: ____________________

____

____

4. (a) Explain where cytoplasm is found in the cell: ____________________

____

(b) Describe what cytoplasm is made up of: ____________________

____

5. Describe two structures, pictured in the cell above, that are associated with storage:

(a) ____________________

____

(b) ____________________

____

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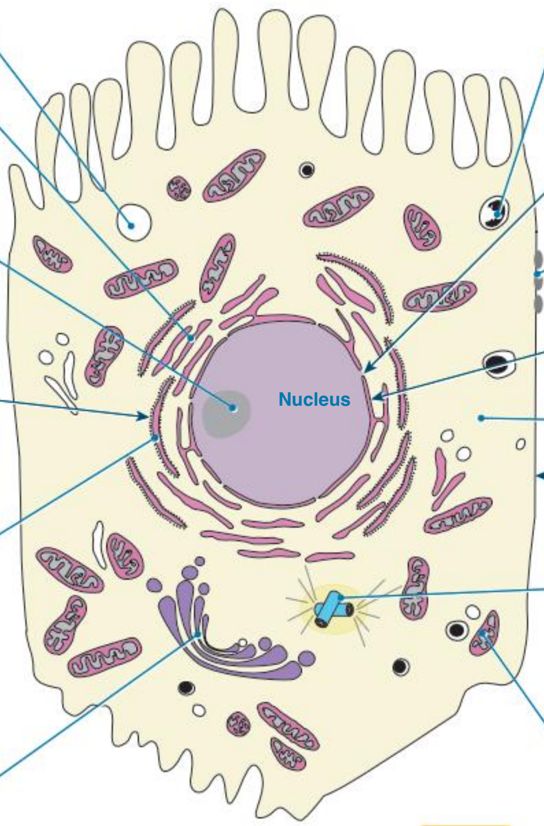
51 Animal Cells

Key Idea: Animal cells are eukaryotic cells. They have many features in common with plant cells, but also have a number of unique features.

Animal cells, unlike plant cells, do not have a regular shape. In fact, some animal cells (such as phagocytes) are able to alter their shape for various purposes (e.g. engulfing foreign material). The diagram below shows the structure and organelles of a liver cell. It contains organelles common to most relatively unspecialised human cells. Note the differences between this cell and the generalised plant cell. The plant cells activity provides further information on the organelles listed here but not described.

Generalised animal cell



Vacuoles: Smaller than those found in plant cells. In animal cells, vacuoles have minor roles in exocytosis and endocytosis.

Smooth endoplasmic reticulum: ER without ribosomes. It is a site for lipid and carbohydrate metabolism, including hormone synthesis.

Nucleolus: A dense, solid structure composed of crystalline protein and nucleic acid. They are involved in ribosome synthesis.

Ribosomes: These small structures may be free in the cytoplasm or associated with the endoplasmic reticulum (ER). Ribosomes in animal cells are 80S ribosomes

Rough endoplasmic reticulum: A site of protein synthesis.The rough ER also synthesises new membranes, growing in place by adding proteins and phospholipids.

Golgi apparatus (20-200 nm): A series of flattened, disc-shaped sacs, stacked one on top of the other and connected with the ER. The Golgi stores, modifies, and packages proteins. It 'tags' proteins so that they go to their correct destination.

Lysosome: A sac bounded by a single membrane. They are pinched off from the Golgi apparatus and contain and transport enzymes that break down food and foreign matter. Lysosomes show little internal structure but often contain fragments of material being broken down. Specialised lysosomes are generally absent from plant cells.

Nuclear pore: A hole in the nuclear membrane allowing the nucleus to communicate with the rest of the cell.

Tight junctions: Join cells together in the formation of tissues.

Nuclear membrane: Double layered

Cytoplasm

Plasma (cell surface) membrane

Centrioles: Structures within a centrosome associated with nuclear division. They are composed of microtubules, but appear as small, featureless particles, 0.25 μm diameter, under a light microscope. They are absent in higher plant cells and some protists.

Mitochondrion (*pl.* mitochondria): An organelle bounded by a double membrane system. The number in a cell depends on its metabolic activity.

1. What is the difference between vacuoles in plant and animal cells? ______________________

____

____

2. Name one structure or organelle present in generalised animal cells but absent from plant cells and describe its function:

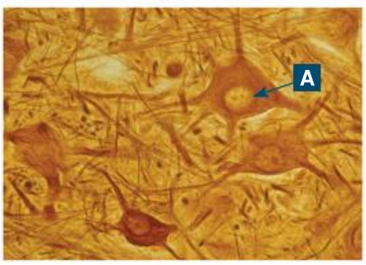
____

3. The two photomicrographs below show several types of animal cells. Identify the features indicated by the letters A-C:

(a) ______________________

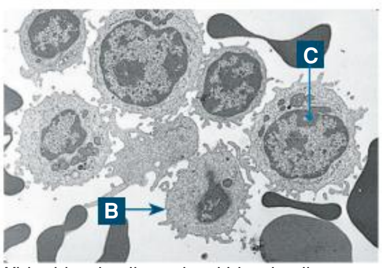
(b) ______________________

(c) ______________________



Photos: EII

Nerve cells in the spinal cord



White blood cells and red blood cells

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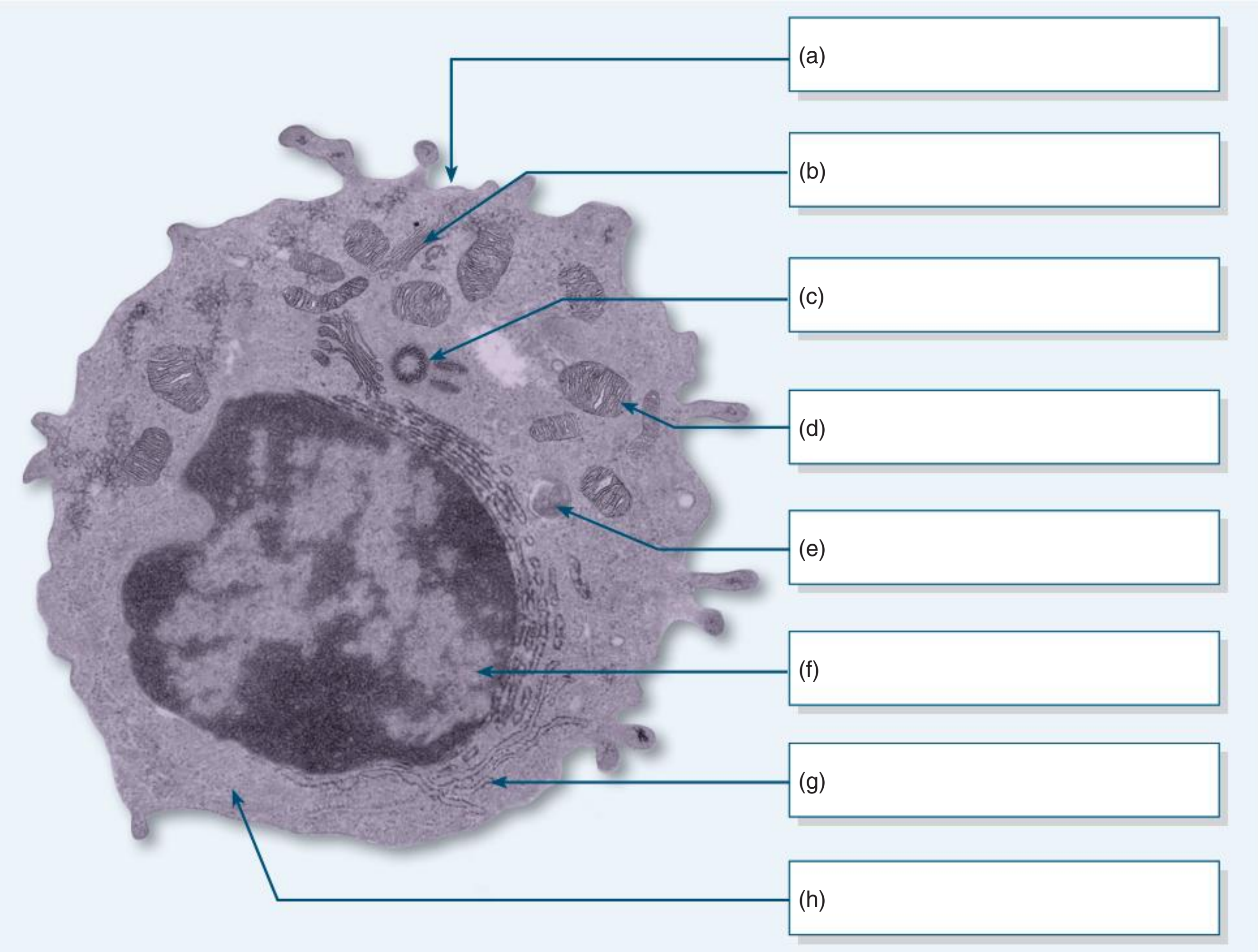
52 Identifying Structures in an Animal Cell

Key Idea: The position of the organelles in an electron micrograph can result in variations in their appearance.

Transmission electron microscopy (TEM) is the most frequently used technique for viewing cellular organelles. When viewing TEMs, the cellular organelles may have quite different appearances depending on whether they are in transverse or longitudinal section.

1. Identify and label the structures in the animal cell below using the following list of terms: *cytoplasm, plasma membrane, rough endoplasmic reticulum, mitochondrion, nucleus, centriole, Golgi apparatus, lysosome*



2. Which of the organelles in the EM above are obviously shown in both transverse and longitudinal section?

3. Why do plants lack any of the mobile phagocytic cells typical of animal cells?

4. The animal cell pictured above is a lymphocyte. Describe the features that suggest to you that:

   (a) It has a role in producing and secreting proteins:

   (b) It is metabolically very active:

5. What features of the lymphocyte cell above identify it as eukaryotic?

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53 Cell Structures and Organelles

Key Idea: Each type of organelle in a cell has a specific role. Not all cell types contain every type of organelle.

The diagram below provides spaces for you to summarise information about the organelles found in eukaryotic cells. The log scale of measurements (top of next page) illustrates the relative sizes of some cellular structures.

1. (a) Name this organelle:

   (b) Structure and location:

   (c) Function:

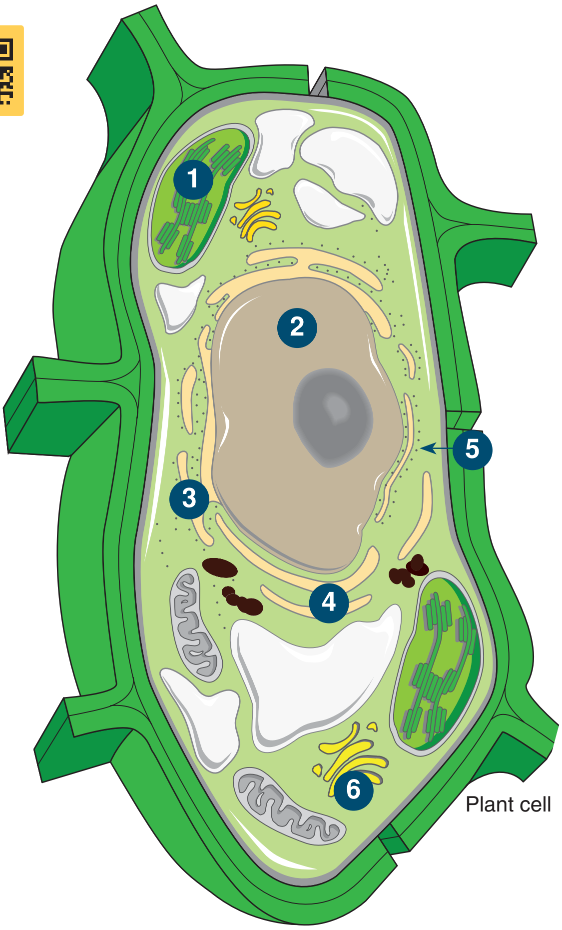
   (d) This organelle is found (circle the correct answer): only in plant cells / only in animal cells / in both plant and animal cells

2. (a) Name this organelle:

   (b) Structure and location:

   (c) Function:

   (d) This organelle is found (circle the correct answer): only in plant cells / only in animal cells / in both plant and animal cells



Plant cell

3. (a) Name this organelle:

   (b) Structure and location:

   (c) Function:

   (d) This organelle is found (circle the correct answer): only in plant cells / only in animal cells / in both plant and animal cells

4. (a) Name this organelle:

   (b) Structure and location:

   (c) Function:

   (d) This organelle is found (circle the correct answer): only in plant cells / only in animal cells / in both plant and animal cells

5. (a) Name this organelle:

   (b) Structure and location:

   (c) Function:

   (d) This organelle is found (circle the correct answer): only in plant cells / only in animal cells / in both plant and animal cells

6. (a) Name this organelle:

   (b) Structure and location:

   (c) Function:

   (d) This organelle is found (circle the correct answer): only in plant cells / only in animal cells / in both plant and animal cells

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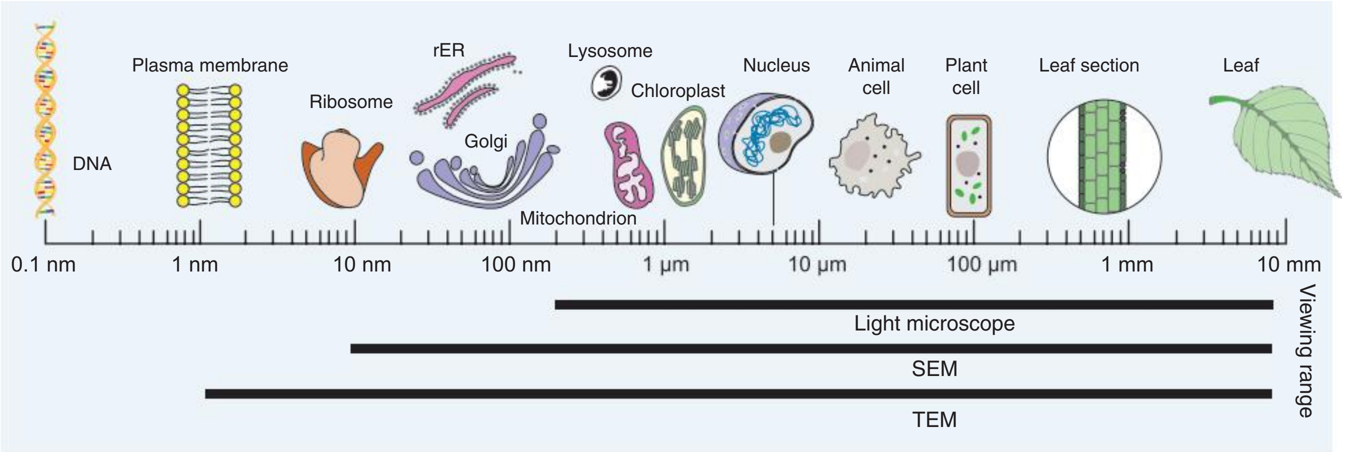

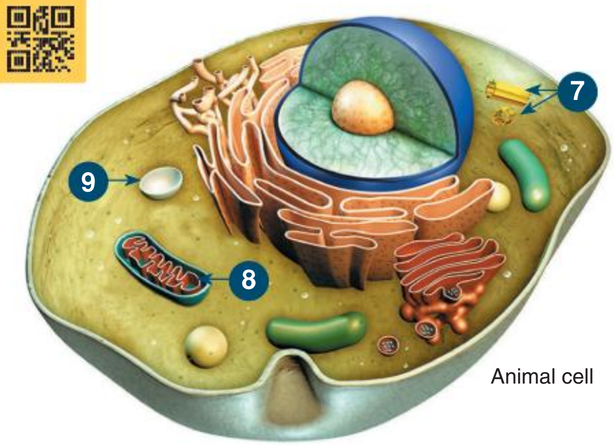

7. (a) Name this organelle:

   (b) Structure and location:

   (c) Function:

   (d) This organelle is found (circle the correct answer): only in plant cells / only in animal cells / in both plant and animal cells

8. (a) Name this organelle:

   (b) Structure and location:

   (c) Function:

   (d) This organelle is found (circle the correct answer): only in plant cells / only in animal cells / in both plant and animal cells

9. (a) Name this organelle:

   (b) Structure and location:

   (c) Function:

   (d) This organelle is found (circle the correct answer): only in plant cells / only in animal cells / in both plant and animal cells

10. Use the scale at the top of the page and the information on previous activities to identify which of the organelles (1-9) can be seen through a light microscope:

11. Identify which of the organelles (1-9) require a TEM (transmission electron microscope) to be seen:

12. Identify one other structure in the plant cell not labelled opposite and describe its function:

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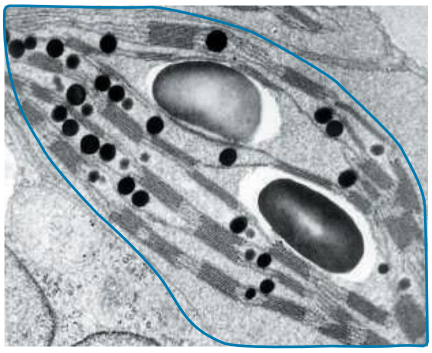
54 Identifying Organelles

Key Idea: Cellular organelles can be identified in electron micrographs by their specific features.

Electron microscopes produce a magnified image at high resolution (distinguish between close together but separate objects). The transmission electron microscope (TEM) images below show the ultrastructure of some organelles.

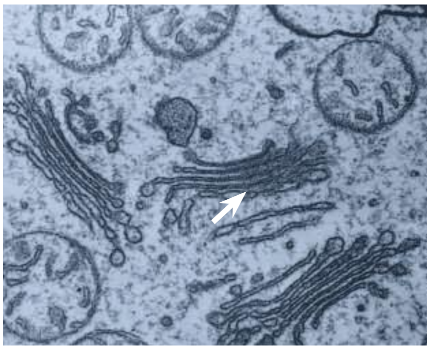


WMU

1. (a) Name the circled organelle: ______________________

   (b) Which kind of cell(s) would this organelle be found in?

   (c) Describe the function of this organelle: ______________________

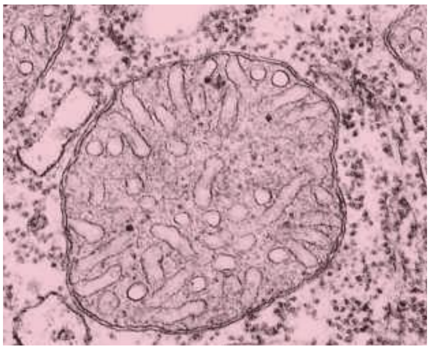


WMU

2. (a) Name this organelle (arrowed): ______________________

   (b) State which kind of cell(s) this organelle would be found in:

   (c) Describe the function of this organelle: ______________________



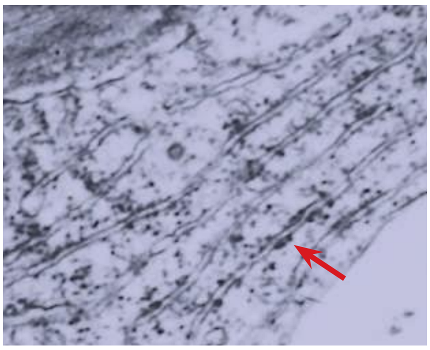
WMU

3. (a) Name the large, circular organelle: ______________________

   (b) State which kind of cell(s) this organelle would be found in:

   (c) Describe the function of this organelle: ______________________

   (d) Label two regions that can be seen inside this organelle.



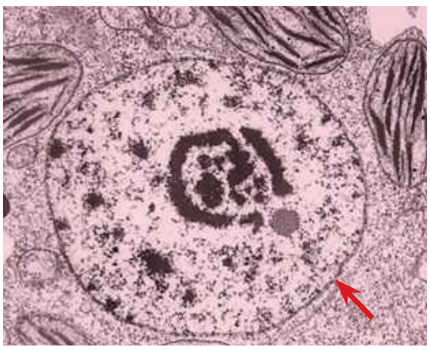
WMU

4. (a) Name and label the ribbon-like organelle in this photograph (arrowed):

   (b) State which kind of cell(s) this organelle is found in: ______________________

   (c) Describe the function of this organelle: ______________________

   (d) Name the dark 'blobs' attached to the organelle you have labelled:



BF

5. (a) Name this large circular organelle (arrowed): ______________________

   (b) State which kind of cell(s) this organelle would be found in:

   (c) Describe the function of this organelle: ______________________

   (d) Label three features relating to this organelle in the photograph.

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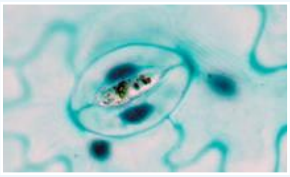
55 Optical Microscopes

Key Idea: Optical microscopes use light focussed through a series of lenses to magnify objects up to several 100 times.

The light (or optical) microscope is an important tool in biology and using it correctly is an essential skill. High power compound light microscopes use visible light and a combination of lenses to magnify objects up to several 100 times. The resolution of light microscopes is limited by the wavelength of light and specimens must be thin and mostly transparent so that light can pass through. No detail will be seen in specimens that are thick or opaque.



Stoma in leaf epidermis

Typical compound light microscope

Word list: *In-built light source, arm, coarse focus knob, fine focus knob, condenser, mechanical stage, eyepiece lens, objective lens*

Specimens viewed with a **compound light microscope** must be thin and mostly transparent so that light can pass through and structures can be seen. Modern microscopes are binocular, i.e. they have two adjustable eyepieces.

What is Magnification?

Magnification refers to the number of times larger an object appears compared to its actual size. Magnification is calculated as follows:

Objective lens power **X** Eyepiece lens power

What is Resolution?

Resolution is the ability to distinguish between close together but separate objects. Examples of high and low resolution for separating two objects viewed under the same magnification are given below.

High resolution

Low resolution

EII

Apple seeds

Dissecting microscope

Word list: *Focus knob, stage, eyepiece lens, objective lens, eyepiece focus*

Dissecting microscopes are a special type of binocular microscope used for observations at low total magnification (X4 to X50), where a large working distance between the objectives and stage is required.

A dissecting microscope has two separate lens systems, one for each eye. Such microscopes produce a 3-D view of the specimen and are sometimes called stereo microscopes for this reason.

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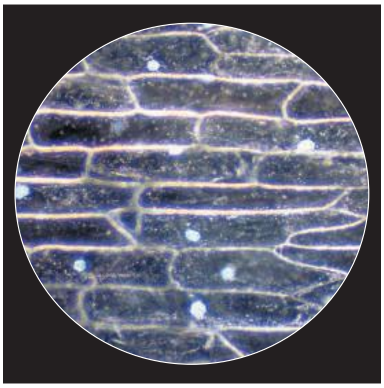
JDG

Dissecting microscopes are used for identifying and sorting organisms, observing microbial cultures, and dissections.

These onion epidermal cells are viewed with standard **bright field** lighting. Very little detail can be seen (only cell walls) and the cell nuclei are barely visible.


Photos: EII

Dark field illumination is excellent for viewing specimens that are almost transparent. The nuclei of these onion epidermal cells are clearly visible.

1. Label the two photographs on the previous page, the compound light microscope (a) to (h) and the dissecting microscope (i) to (m). Use words from the lists supplied for each image.

2. Determine the magnification of a microscope using:

   (a) 15 X eyepiece and 40 X objective lens: ____________ (b) 10 X eyepiece and 60 X objective lens: ______________

3. Describe the main difference between a compound light microscope and a dissecting microscope: ________________

   ____

   ____

4. What type of microscope would you use to:

   (a) Count stream invertebrates in a sample: ______________ (b) Observe cells in mitosis: ______________________

5. (a) Distinguish between **magnification** and **resolution**: ____

   ____

   (b) Explain the benefits of a higher resolution: ____

   ____

   ____

6. Below is a list of ten key steps taken to set up a microscope and optimally view a sample. The steps have been mixed up. Put them in their **correct order** by numbering each step:

☐ Focus and centre the specimen using the high objective lens. Adjust focus using the fine focus knob only.

☐ Adjust the illumination to an appropriate level by adjusting the iris diaphragm and the condenser. The light should appear on the slide directly below the objective lens, and give an even amount of illumination.

☐ Rotate the objective lenses until the shortest lens is in place (pointing down towards the stage).
This is the lowest / highest power objective lens (delete one).

☐ Place the slide on the microscope stage. Secure with the sample clips.

☐ Fine tune the illumination so you can view maximum detail on your sample.

☐ Focus and centre the specimen using the medium objective lens. Focus firstly with the coarse focus knob, then with the fine focus knob (if needed).

☐ Turn on the light source.

☐ Focus and centre the specimen using the low objective lens. Focus firstly with the coarse focus knob, then with the fine focus knob.

☐ Focus the eyepieces to adjust your view.

☐ Adjust the distance between the eyepieces so that they are comfortable for your eyes.

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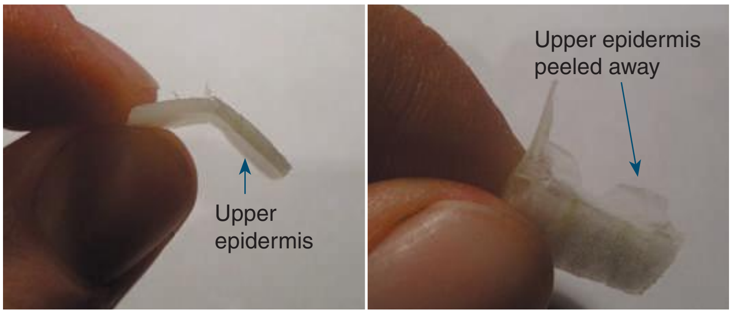
56 Preparing a Slide

Key Idea: Correctly preparing and mounting a specimen on a slide are important if structures are to be seen clearly under a microscope. A wet mount is suitable for most slides.

Specimens are usually prepared in some way before viewing in order to highlight features and reveal details. A wet mount is a temporary preparation in which a specimen and a drop of fluid are trapped under a thin coverslip. Wet mounts are used to view thin tissue sections, live microscopic organisms, and suspensions such as blood. A wet mount improves a sample's appearance and enhances visible detail. Sections must be made very thin for two main reasons. A thick section stops light shining through making it appear dark when viewed. It also ends up with too many layers of cells, making it difficult to make out detail.

Preparing a specimen

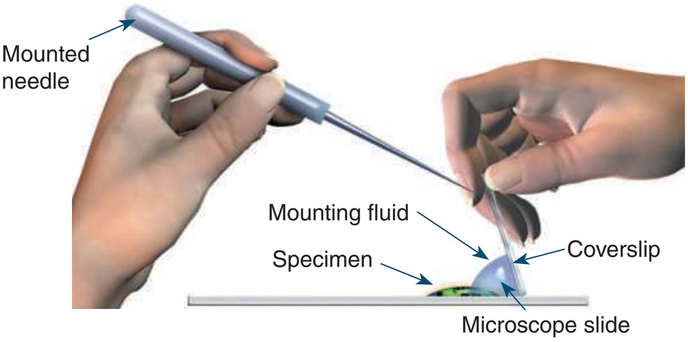


These photos KP

Onions make good subjects for preparing a simple wet mount. A square segment is cut from a thick leaf of the bulb. The segment is then bent towards the upper epidermis and snapped so that just the epidermis is left attached. The epidermis can then be peeled off to provide a thin layer of cells for viewing.

Sections through stems or other soft objects are made with a razor blade or scalpel and must be very thin. Cutting at a slight angle produces a wedge shape with a thin edge. Ideally, specimens should be set in wax before sectioning. This stops crushing and makes it easy to cut the specimen.

Mounting a specimen



The thin layer is placed in the centre of a clean glass microscope slide and covered with a drop of mounting liquid (e.g. water, glycerol, or stain). To cover it for viewing, a mounted needle is used as support and the coverslip is lowered gently over the specimen. This avoids including air in the mount.

Viewing

Locate the specimen or region of interest at the lowest magnification. Focus using the lowest magnification first, before switching to the higher magnifications.

1. Why must sections viewed under a microscope be very thin? ______________________

____

2. Why do you think the specimen is covered with a coverslip? ______________________

____

____

3. Why would no chloroplasts be visible in an onion epidermis cell slide? ______________________

____

4. Why is it necessary to focus on the lowest magnification first, before switching to higher magnifications? ______________________

____

____

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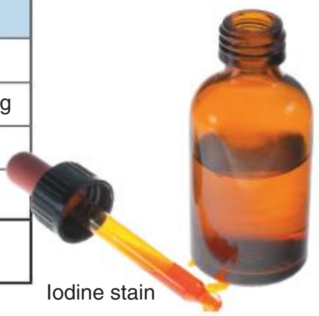
57 Staining a Slide

Key Idea: Staining material to be viewed under a microscope can make it easier to distinguish particular cell structures.

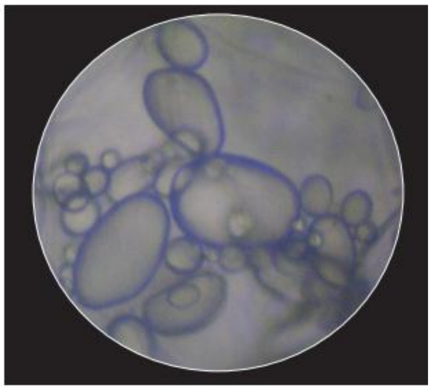
Stains and dyes can be used to highlight specific components or structures. Most stains are **non-viable**, and are used on dead specimens, but harmless **viable stains** can be applied to living material. Stains contain chemicals that interact with molecules in the cell. Some stains bind to a particular molecule making it easier to see where those molecules are. Others cause a change in a target molecule, which changes their colour, making them more visible.

Some commonly used stains

Stain	Final colour	Used for
Iodine solution	blue-black	Starch
Crystal violet	purple	Gram staining
Aniline sulfate	yellow	lignin
Methylene blue	blue	Nuclei
Hematoxylin and eosin (H&E)	H=dark blue/violet E=red/pink	H=Nuclei E=Proteins

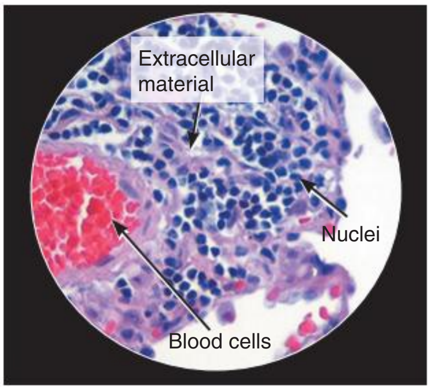


Iodine stain



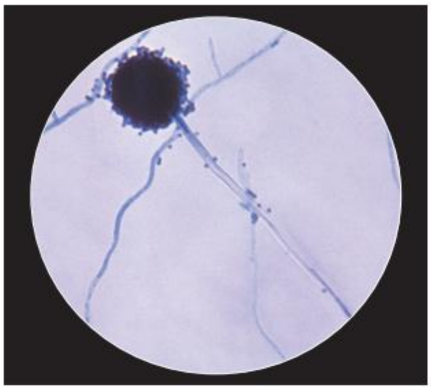
Mnolf

Iodine stains starch-containing organelles, such as potato amyloplasts, blue-black.



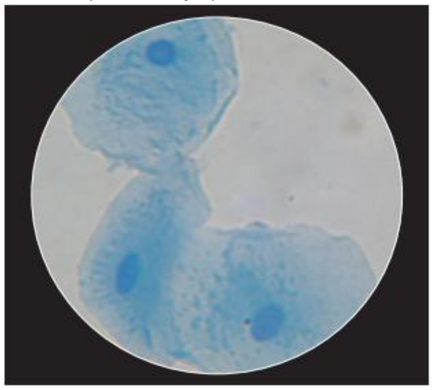
PloS

H&E stain is one of the most common stains for animal tissues. Nuclei stain dark blue, whereas proteins, extracellular material, and red blood cells stain pink or red.



Mnolf

Vital (viable) stains do not immediately harm living cells. Trypan blue is a vital stain that stains dead cells blue but is excluded by live cells. It is also used to study fungal hyphae.

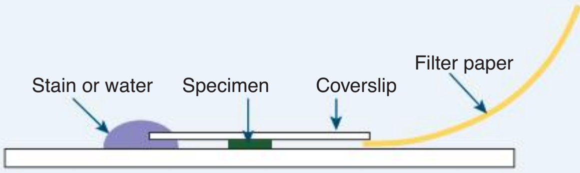


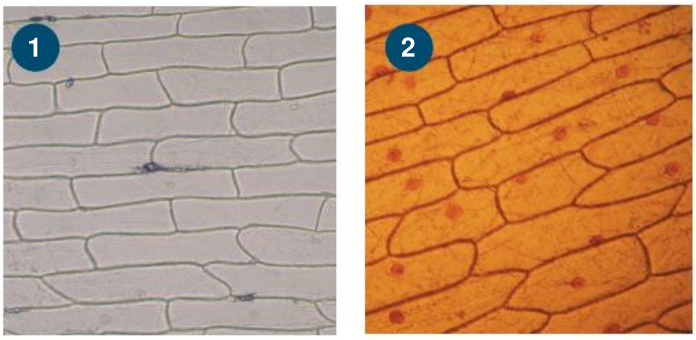
CDC: Dr Lucille K. Georg

Methylene blue is a common temporary stain for animal cells, such as these cheek cells. It stains DNA and so makes the nuclei more visible.

How to apply a simple stain

If a specimen is already mounted, a drop of stain can be placed at one end of the coverslip and drawn through using filter paper (below). Water can be drawn through in the same way to remove excess stain.





Photos: Ell

The light micrographs 1 and 2 (above) illustrate how the use of a stain can enhance certain structures. The left image (1) is unstained and only the cell wall is easily visible. Adding iodine (2) makes the cell wall and nuclei stand out.

1. What is the main purpose of using a stain? ______________________________

____

2. What is the difference between a viable and non-viable stain? ______________________________

____

3. Identify a stain that would be appropriate for distinguishing each of the following:

(a) Live vs dead cells: ______________ (c) Lignin in a plant root section: ______________

(b) Red blood cells in a tissue preparation: ______________ (d) Nuclei in cheek cells: ______________

ISBN: 978-1-927309-83-4

58 Calculating Linear Magnification

Key Idea: Magnification is how much larger an object appears compared to its actual size. It can be calculated from the ratio of image height to object height.

Microscopes produce an enlarged (magnified) image of an object allowing it to be observed in greater detail than is possible with the naked eye. **Magnification** refers to the number of times larger an object appears compared to its actual size. Linear magnification is calculated by taking a ratio of the image height to the object's actual height. If this ratio is greater than one, the image is enlarged. If it is less than one, it is reduced. To calculate magnification, all measurements are converted to the same units. Often, you will be asked to calculate an object's actual size, in which case you will be told the size of the object and the magnification.

Calculating linear magnification: A worked example

1.0 mm

1 Measure the body length of the bed bug image (right). Your measurement should be 40 mm (***not*** including the body hairs and antennae).

2 Measure the length of the scale line marked 1.0 mm. You will find it is 10 mm long. The magnification of the scale line can be calculated using equation 1 (below right).

The magnification of the scale line is **10** (10 mm ÷ 1 mm)

**NB: The magnification of the bed bug image will also be 10x because the scale line and image are magnified to the same degree.*

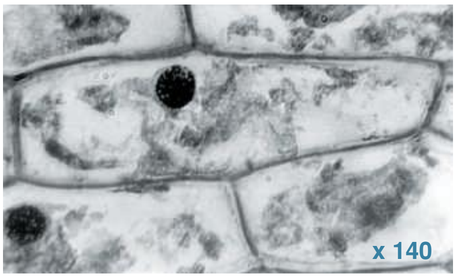
3 Calculate the actual (real) size of the bed bug using equation 2 (right):

The actual size of the bed bug is **4 mm** (40 mm ÷ 10 x magnification)

Microscopy equations

$$1.\ \text{Magnification} = \frac{\text{measured size of the object}}{\text{actual size of the object}}$$

$$2.\ \text{Actual object size} = \frac{\text{size of the image}}{\text{magnification}}$$

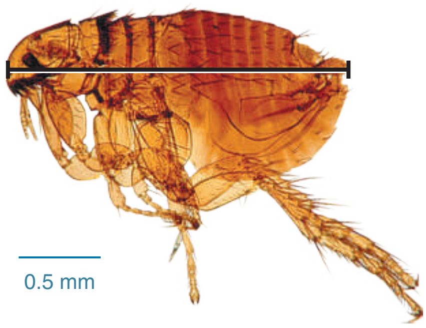


1. The bright field microscopy image on the left is of onion epidermal cells. The measured length of the onion cell in the centre of the photograph is 52,000 µm (52 mm). The image has been magnified 140 x. Calculate the actual size of the cell:

____

____

____



2. The image of the flea (left) has been captured using light microscopy.

   (a) Calculate the magnification using the scale line on the image:

   ____

   ____

   ____

   (b) The body length of the flea is indicated by a line. Measure along the line and calculate the actual length of the flea:

   ____

   ____

   ____

3. The image size of the *E.coli* cell (left) is 43 mm, and its actual size is 2 µm. Using this information, calculate the magnification of the image:

____

____

____

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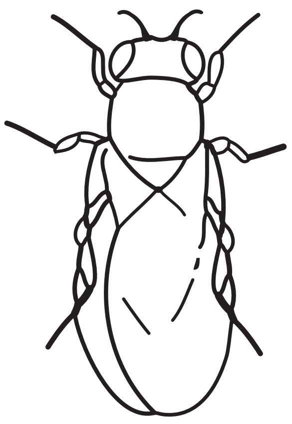
59 Biological Drawings

Key Idea: Good biological drawings provide an accurate record of the specimen you are studying and enable you to make a record of its important features.

Drawing is a very important skill to have in biology. Drawings record what a specimen looks like and give you an opportunity to record its important features. Often drawing something will help you remember its features at a later date (e.g. in a test). Annotated drawings provide explanatory notes about the labelled structures, while plan diagrams label the main structures observed, but provide no additional detail.

- Biological drawings require you to pay attention to detail. It is very important that you draw what you actually see, and not what you think you should see.
- Biological drawings should include as much detail as you need to distinguish different structures and types of tissue, but avoid unnecessary detail which can make your drawing confusing.
- Attention should be given to the symmetry and proportions of your specimen. Accurate labeling, a statement of magnification or scale, the view (section type), and type of stain used (if applicable) should all be noted on your drawing.
- Some key points for making good biological drawing are described on the example below. The drawing of *Drosophila* (right) is well executed but lacks the information required to make it a good biological drawing.



This drawing of *Drosophila* is a fair representation of the animal, but has no labels, title, or scale.

All drawings must include a title. Underline the title if it is a scientific name.

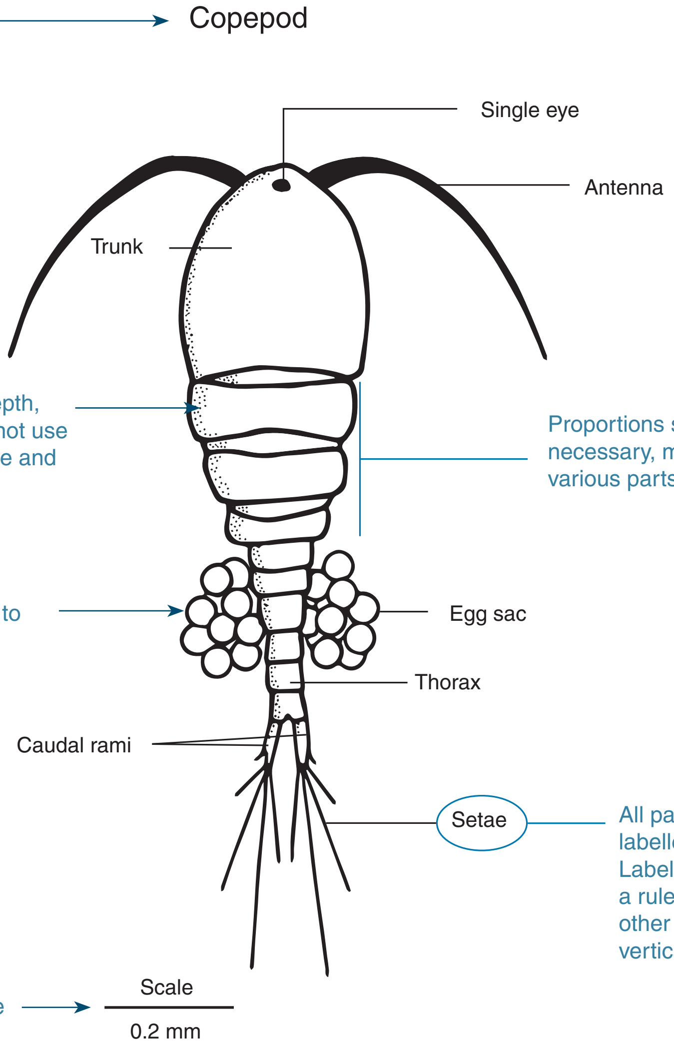
Centre your drawing on the page, not in a corner. This will leave room to place labels around the drawing.

If you need to represent depth, use stippling (dotting). Do not use shading as this can smudge and obscure detail.

Use simple, narrow lines to make your drawings.

Use a sharp pencil to draw with. Make your drawing on plain white paper.

Your drawing must include a scale or magnification to indicate the size of your subject.



Proportions should be accurate. If necessary, measure the lengths of various parts with a ruler.

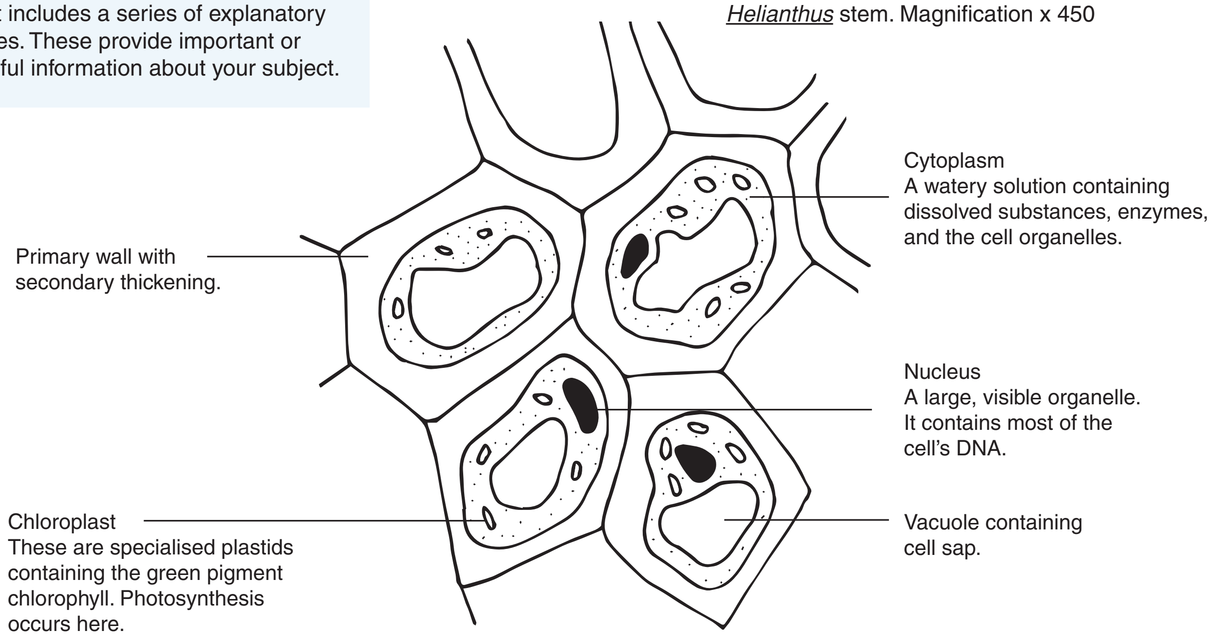
All parts of your drawing must be labelled accurately. Labeling lines should be drawn with a ruler and should not cross over other label lines. Try to use only vertical or horizontal lines.

ISBN: 978-1-927309-83-4

Annotated diagrams

An annotated diagram is a diagram that includes a series of explanatory notes. These provide important or useful information about your subject.

Transverse section through collenchyma of *Helianthus* stem. Magnification x 450

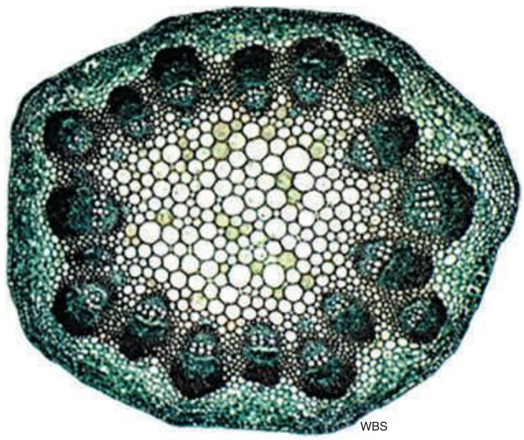


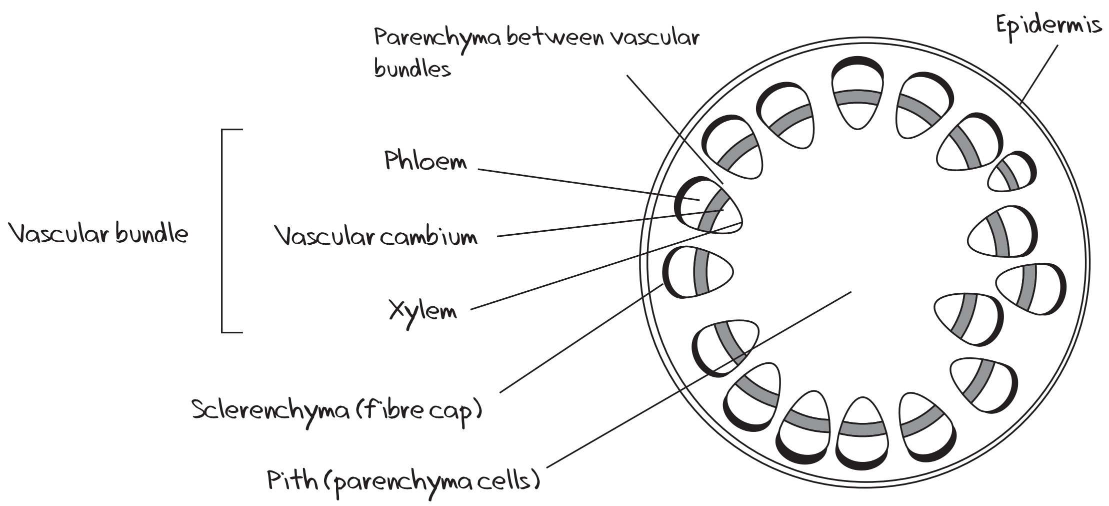
Plan diagrams

Plan diagrams are drawings made of samples viewed with the naked eye, hand lens, or under a microscope at low or medium power. They are used to show the distribution of the different tissue types in a sample without any cellular detail. The tissues are identified, but no detail about the cells within them is included.

The example here shows a plan diagram produced after viewing a light micrograph of a transverse section through a dicot stem.

Light micrograph of a transverse section through a dicot stem.





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60 Observing and Recording Using a Microscope

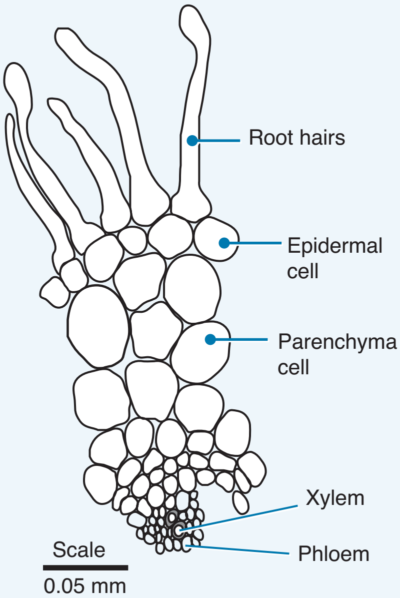
Key Idea: Attention to detail is vital when making accurate and useful biological drawings.

In this activity, you will practise the skills required to translate what is viewed into a good biological drawing.

Above: Use relaxed viewing when drawing at the microscope. Use one eye (the left for right handers) to view and the right eye to look at your drawing.

Above: Light micrograph Transverse section (TS) through a *Ranunculus* root.

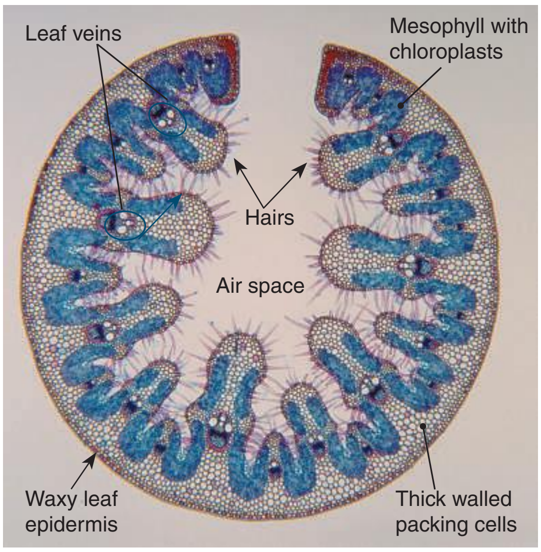
Right: A biological drawing of the same section.



1. During your course, you will study the features of cells and also make an investigation related to survival or an organism or species. You may need to identify and draw features of plant or animal tissues with a light microscope. Generally, only large organelles such as the nucleus and chloroplasts are easily seen at the magnifications typical of school microscopes (x 400).

   In the space right, make a biological drawing of your own specimen or slide, or practise your drawing by making a plan diagram of the image below.

   Below: A light micrograph of a leaf from the beach grass *Ammophila* below. The leaf is rolled inwards to reduce water loss.



EII

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61 KEY TERMS AND IDEAS: Did You Get It?

1. Test your vocabulary by matching each term to its definition, as identified by its preceding letter code.

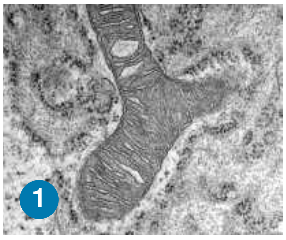
Term		Code	Definition
cell wall	....	A	Organelle responsible for producing the cell's ATP. It appears oval in shape with an outer double membrane and a convoluted interior membrane. Contains its own circular DNA.
chloroplast	....	B	With reference to cells, lacking a distinct nucleus and with no membrane-bound organelles DNA is present as a single, circular, naked chromosome.
cytoplasm	....	C	Cell types with a distinct membrane-bound nucleus and membrane-bound organelles.
eukaryotic	....	D	The ability to distinguish between close together but separate objects.
magnification	....	E	The watery contents of the cell within the plasma membrane, but excluding the contents of the nucleus.
mitochondrion	....	F	A structural and functional part of the cell usually bound within its own membrane. Examples include the mitochondria and chloroplasts.
nucleus	....	G	Membrane-bound region within a eukaryotic cell where the chromosomes are found.
organelle	....	H	An organelle found in photosynthetic organisms such as plants, which contains chlorophyll and in which the reactions of photosynthesis take place.
prokaryotic	....	I	A structure, present in plants and bacteria, which is found outside the plasma membrane and gives rigidity to the cell.
resolution	....	J	How many times larger an image is than the original object.

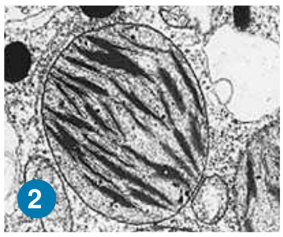
2. (a) Identify organelle 1: ______________________

(b) The organelle in (a) is found in a plant cell / animal cell / both plant and animal cells (circle the correct answer).

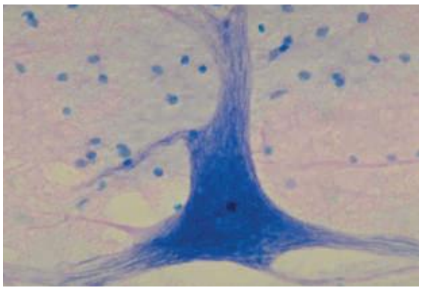
(c) Identify organelle 2: ______________________

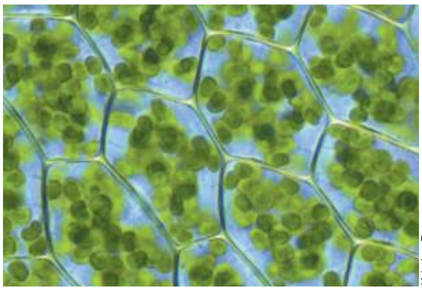
(d) The organelle in (c) is found in a plant / animal cell / plant and animal cell (circle the correct answer).



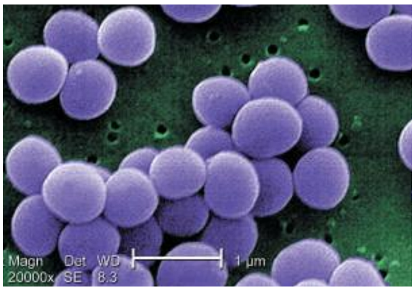


3. For each of the following images of cells, identify the cell type (plant, animal, bacterial), give a brief reason for your decision and note any organelles or structures visible.





Kristian Peters



CDC

(a) ______________________

____

____

(b) ______________________

____

____

(c) ______________________

____

____

4. Match the start of the sentences on the left below to the end of the sentences on the right:

Cells are the basic...	...such as photosynthesis or respiration.
A cell is enclosed by a plasma membrane...	…a cell wall of cellulose.
Plant cells have…	...do not contain membrane-bound organelles.
Animal cells do...	...units of life.
Eukaryotic cells contain many different types of organelle...	....not have a cell wall.
Each organelle carries out a specific function in the cell...	...some of which are composed of membranes.
Prokaryotic cells...	...made of a phospholipid bilayer

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UNIT 1
Topic 1

Internal Membranes and Enzymes

Key terms

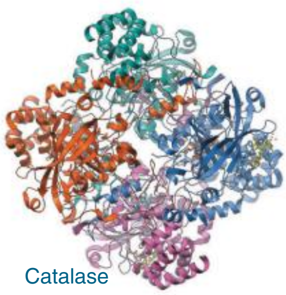
activation energy
active site
anabolic reaction
catabolic reaction
catalyst
coenzyme
cofactor
denaturation
enzyme
enzyme-product complex
enzyme-substrate complex
enzyme inhibition
extracellular
induced fit model
intracellular
irreversible inhibitor
lock-and-key model
metabolic pathway
metabolism
optimum (for enzyme)
reversible inhibitor
specificity

Activity number

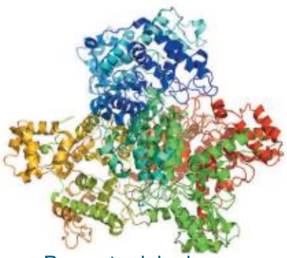
Enzymes are protein catalysts

Key skills and knowledge

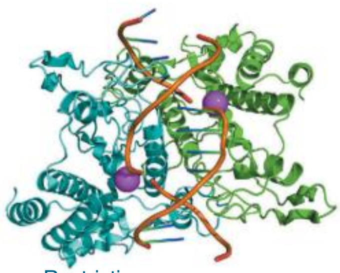
- ☐ 1 Recognise that biochemical processes are controlled and regulated by a series of specific enzymes and that all the biochemical reactions in living things (both intracellular and extracellular) constitute metabolism. **62 64 68**
- ☐ 2 Distinguish between anabolic and catabolic reactions and give examples of each.
- ☐ 3 Describe models for enzyme function, including reference to the enzyme-substrate complex, enzyme-product complex, and product formation. **63**
- ☐ 4 *SHE* Compare and contrast the induced-fit and the lock-and-key models of enzyme function. Why did the lock and key model change? **63**
- ☐ 5 Explain how enzymes catalyse reactions by lowering the activation energy and identify this on a plot of the progress of the reaction against the free energy. Describe the structure and role of the active site, explaining its importance to the specificity of the enzyme to its substrate(s). **64**
- ☐ 6 Recognise that many enzymes require cofactors in order to function and that these may be inorganic ions or organic molecules (coenzymes) such as vitamins. **64**



Catalase
Vossman cc 3.0



Pyruvate dehydrogenase
Fontanna GC cc 3.0



Restriction enzyme

Factors affecting enzyme activity

Key skills and knowledge

- ☐ 7 Explain how enzyme reaction rates can be affected by pH, temperature, and the concentrations of reactants (substrates) and products. Recognise that enzymes, like all proteins, can be denatured by high temperatures or extremes of pH and relate this to the loss of their functional tertiary structure. **65**
- ☐ 8 Using examples, describe the effects of inhibitors on the rate of enzyme-controlled reactions. Include reference to competitive and non-competitive inhibition and identify these on graphs of reaction rate vs substrate concentration. **66**
- ☐ 9 *PRAC* Investigate factors affecting enzyme reaction rates, e.g. the effect of lead nitrate (an inhibitor) or pH on the activity of peroxidase. **67**
- ☐ 10 Distinguish between reversible and non-reversible inhibitors. Explain the role of reversible end-product inhibition in regulating biochemical pathways. **66 68**

Enzymes may be associated with membranes

Key skills and knowledge

- ☐ 11 Recall from the previous chapters that eukaryotic cells contain membranous organelles. Explain, using an example, how the arrangement of internal membranes controls biochemical processes and contributes to the functional efficiency of the cell. **69**
- ☐ 12 Explain, using examples, how increasing the surface area of the cell itself can provide more sites for enzyme attachment and so increase reaction rates (e.g. the microvilli of intestinal epithelial cells). **69**

62 Enzymes

Key Idea: Enzymes are biological catalysts. The active site is critical to this functional role.

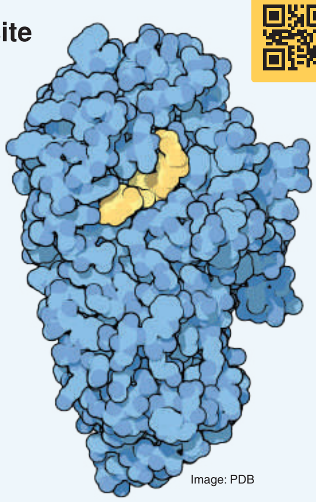
Most enzymes are globular proteins. Enzymes are biological catalysts because they speed up biochemical reactions, but the enzyme itself remains unchanged. The substrate in a reaction binds to a region of the enzyme called the active site, which is formed by the precise folding of the enzyme's amino acid chain. Enzymes control metabolic pathways. One enzyme will act on a substance to produce the next reactant in a pathway, which will be acted on by a different enzyme.

The active site

An enzyme acts on a specific chemical called a substrate. The substrate binds to a specific part of the enzyme called the **active site**.

The shape and chemistry of the active site is specific to an enzyme and is a function of the polypeptide's tertiary structure (the way the protein folds up). The amylase shown here breaks starch (a large molecule made of repeating glucose units) into smaller pieces with 2-3 glucose units.

Extremes of temperature or pH can alter the enzyme's active site and lead to loss of function. This process is called **denaturation**.

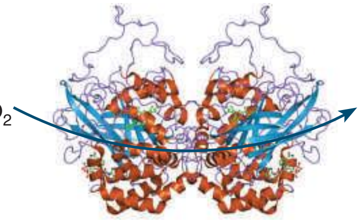


Amylase (blue) with bound glucose (yellow) at the active site

Enzymes can be intracellular or extracellular

Enzymes can be defined based on where they are produced relative to where they are active.

An **intracellular enzyme** is an enzyme that performs its function within the cell that produces it. Most enzymes are intracellular enzymes, e.g. respiratory enzymes.
Example: Catalase.
Many metabolic processes produce hydrogen peroxide, which is harmful to cells. Catalase converts hydrogen peroxide into water and oxygen (below) to prevent damage to cells and tissues.



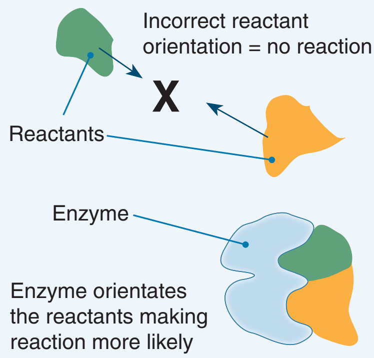
Catalase

An **extracellular enzyme** is an enzyme that functions outside the cell from which it originates (i.e. it is produced in one location but active in another).
Examples: Amylase and trypsin.
Amylase is a digestive enzyme produced in the salivary glands and pancreas in humans. However, it acts in the mouth and small intestine respectively to hydrolyse starch into sugars.

Trypsin is a protein-digesting enzyme and hydrolyses the peptide bond immediately after a basic residue (e.g. arginine). It is produced in an inactive form (called trypsinogen) and secreted into the small intestine by the pancreas. It is activated in the intestine by the enzyme enteropeptidase to form trypsin. Active trypsin can convert more trypsinogen to trypsin.

Substrates collide with an enzyme's active site

For a reaction to occur reactants must collide with sufficient speed and with the correct orientation. Enzymes enhance reaction rates by providing a site for reactants to come together in such a way that a reaction will occur. They do this by orientating the reactants so that the reactive regions are brought together. They may also destabilise the bonds within the reactants making it easier for a reaction to occur.



1. (a) What is meant by the active site of an enzyme and relate it to the enzyme's tertiary structure: ____________________

____

____

____

(b) Why are enzymes specific to one substrate (or group of closely related substrates)? ____________________

____

____

2. How do substrate molecules come into contact with an enzyme's active site? ____________________

____

3. (a) Suggest why digestion (the breakdown of large macromolecules) is largely performed by extracellular enzymes:

____

(b) Why would an extracellular enzyme be produced and secreted in an inactive form? ____________________

____

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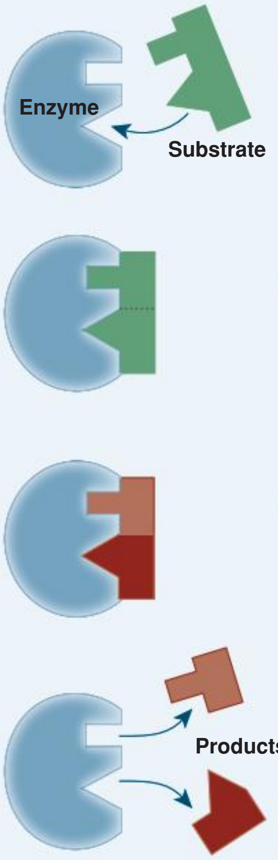
63 Models of Enzyme Activity

Key Idea: Enzymes catalyse reactions by providing a reaction site for a substrate. The model that describes the behaviour of enzymes the best is the induced fit model.

The initial model of enzyme activity was the lock and key model proposed by Emil Fischer in the 1890s. Fischer proposed enzymes were rigid structures, similar to a lock, and the substrate was the key. While some aspects of Fischer's model were correct, for example, substrates align with enzymes in a way that is likely to make a reaction more likely, the model has been adapted as techniques to study molecular structures have developed. The current 'induced-fit' model of enzyme function is supported by studies of enzyme inhibitors, which show that enzymes are flexible and change shape when interacting with the substrate.

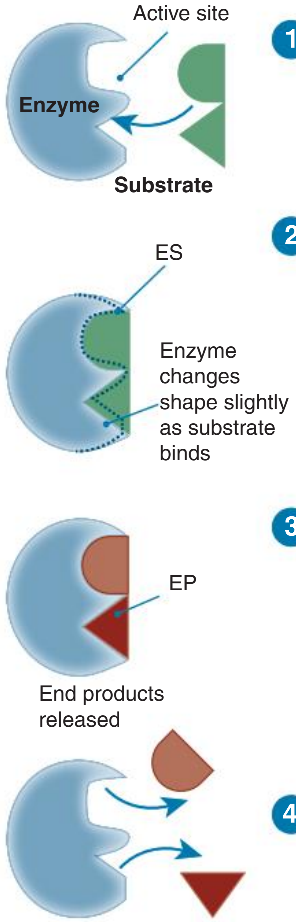
The lock and key model of enzyme function



1. The substrate molecule is drawn into the active site of the enzyme. The enzyme's active site does not change shape.
2. The enzyme-substrate (ES) complex is formed.
3. The enzyme reaction takes place to form the enzyme-product (EP) complex.
4. The products are released from the enzyme. Note there has been no change in the shape of the active site throughout the reaction.

The **lock and key model** proposed in 1894 suggested that the (perfectly fitting) substrate was simply drawn into a matching site on the enzyme molecule. If the substrate did not perfectly fit the active site, the reaction did not proceed. This model was supported by early X-ray crystallography studies but has since been modified to recognise the flexibility of enzymes (the induced fit model).

The current induced fit model



1. A substrate molecule is drawn into the enzyme's active site, which is like a cleft into which the substrate molecule(s) fit.
2. The enzyme changes shape as the substrate binds an enzyme-substrate (ES) complex. The shape change makes the substrate more amenable to alteration. In this way, the enzyme's interaction with its substrate is best regarded as an induced fit.
3. The ES interaction results in an intermediate enzyme-product (EP) complex. The substrate becomes bound to the enzyme by weak chemical bonds, straining bonds in the substrate and allowing the reaction to proceed more readily.
4. The end products are released and the enzyme returns to its previous shape.

Once the substrate enters the active site, the shape of the active site changes to form an active complex. The formation of an ES complex strains substrate bonds and lowers the energy required to reach the transition state. The **induced-fit model** is supported by X-ray crystallography, chemical analysis, and studies of enzyme inhibitors, which show that enzymes are flexible and change shape when interacting with the substrate.

1. Describe the key features of the 'lock and key' model of enzyme action and explain its deficiencies as a working model:

2. How does the current 'induced fit' model of enzyme action differ from the lock and key model?

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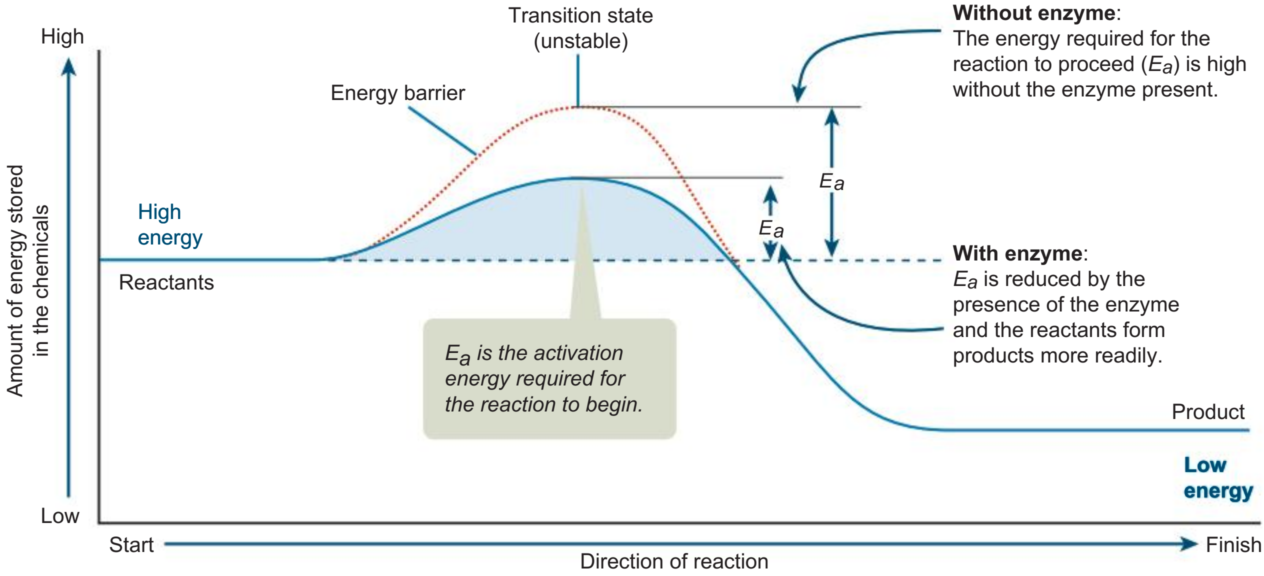
64 How Enzymes Work

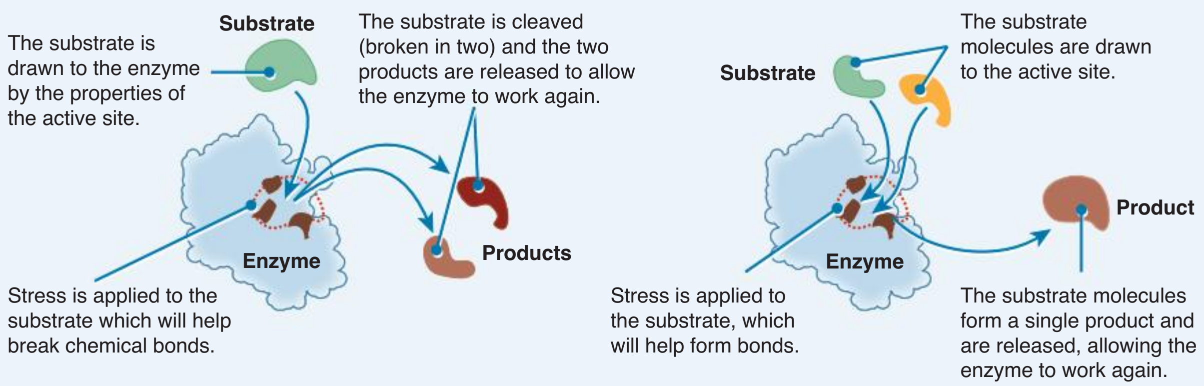
Key Idea: Enzymes increase the rate of biological reactions by lowering the reaction's activation energy.

Chemical reactions in cells are accompanied by energy changes. The amount of energy released or taken up is directly related to the tendency of a reaction to run to completion (for all the reactants to form products). Any reaction needs to raise the energy of the substrate to an unstable transition state before the reaction will proceed (below). The amount of energy needed to do this is the **activation energy** (E_a). Enzymes lower the E_a by destabilising bonds in the substrate so that it is more reactive. Enzyme reactions can break down a single substrate molecule into simpler substances (catabolic reactions), or join two or more substrate molecules together (anabolic reactions).

Lowering the activation energy

The presence of an enzyme simply makes it easier for a reaction to take place. All catalysts speed up reactions by influencing the stability of bonds in the reactants. They may also provide an alternative reaction pathway, thus lowering the activation energy (E_a) needed for a reaction to take place (see the graph below).





Enzymes can catalyse the breakdown of molecules

Some enzymes can cause a single substrate molecule to be drawn into the active site. Chemical bonds are broken, causing the substrate molecule to break apart to become two separate molecules. Reactions that break down complex molecules into simpler ones are called catabolic reactions and involve a net release of energy (they are exergonic). Example: *digestion*.

Enzymes can catalyse the building of molecules

Some enzymes can cause two substrate molecules to be drawn into the active site. Chemical bonds are formed, causing the two substrate molecules to form bonds and become a single molecule. Reactions that build more complex molecules and structures from simpler ones are called anabolic reactions and involve a net use of energy (they are endergonic). Example: *protein synthesis*.

1. Why do reactants need energy added to them in order for them to react? ______________________________

____

____

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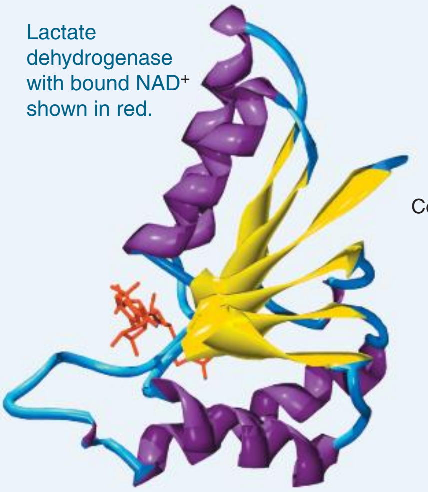
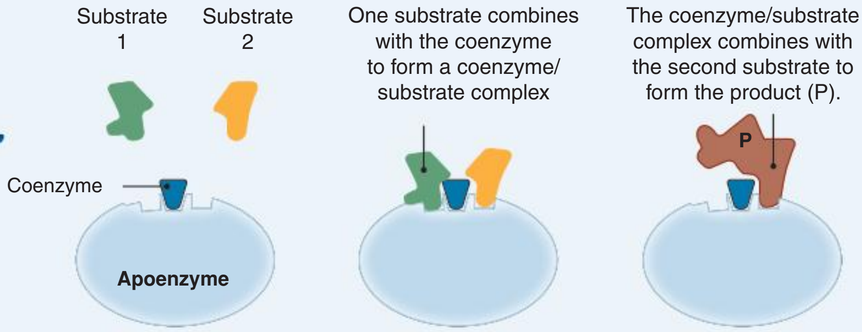
Enzymes and cofactors

Nearly all enzymes are made of protein. Some enzymes are functional protein-only molecules, but many require additional non-protein components, called **cofactors**, to function. Cofactors can be subclassified as either inorganic ions (e.g. Zn^{2+}) or complex organic molecules called coenzymes (many of which are vitamins). Many enzymes need several cofactors in order to function. Where a cofactor is needed for enzyme function, the enzyme (protein) component is called the apoenzyme. The cofactor often completes the active site or makes the active site more reactive by assisting enzyme-substrate interactions.





If cofactors are not permanently bound to the enzyme, they can detach after the reaction to participate in other reactions. Neither the apoenzyme nor the cofactor has catalytic activity on its own. **Example**: dehydrogenases + NAD. NAD is the coenzyme form of the vitamin niacin (B_3). Many coenzymes are vitamin derivatives.

2. How do enzymes lower the activation energy for a reaction? ______________________________

____

____

____

3. Why are enzymes referred to as "biological catalysts"? ______________________________

____

____

4. Describe the difference between digestion and protein synthesis in terms of the energy released or required : __________

____

____

____

5. What is a cofactor? ______________________________

____

____

6. Describe the difference between the two different broad categories of cofactors: ______________________________

____

____

____

7. How do cofactors enable an enzyme's catalytic activity? ______________________________

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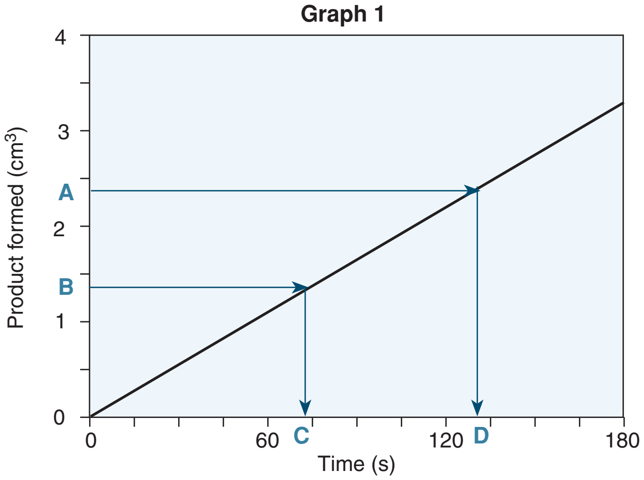
65 Enzyme Kinetics

Key Idea: Enzymes operate most effectively within a narrow range of conditions. The rate of enzyme-catalysed reactions is influenced by both enzyme and substrate concentration.

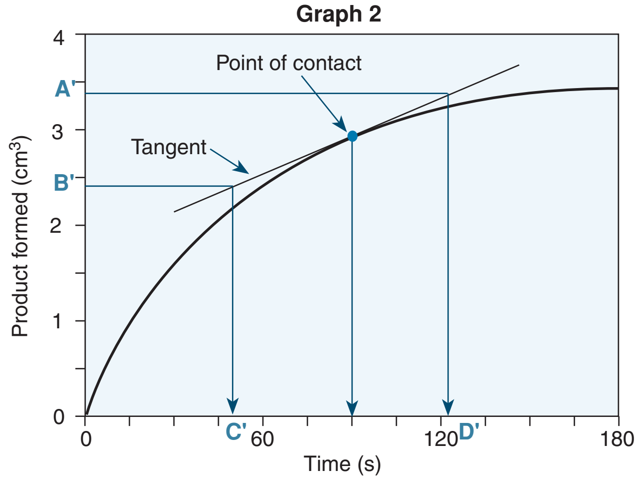
Enzymes usually have an optimum set of conditions (e.g. of pH and temperature) under which their activity is greatest. Many plant and animal enzymes show little activity at low temperatures. Enzyme activity increases with increasing temperature, but falls off after the optimum temperature is exceeded and the enzyme is denatured. Extremes in pH can also cause denaturation. Within their normal operating conditions, enzyme reaction rates are influenced by enzyme and substrate concentration in a predictable way.

Graph 1

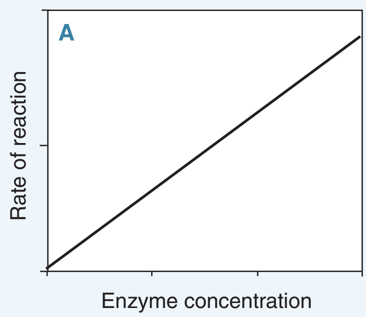


The rate of a reaction can be calculated from the amount of product produced during a given time period. For a reaction in which the rate does not vary (graph 1) the reaction rate calculated at any one point in time will be the same. For example: B/C = A/D = A-B/D-C = (Δp/Δt) (the change in product divided by the change in time).

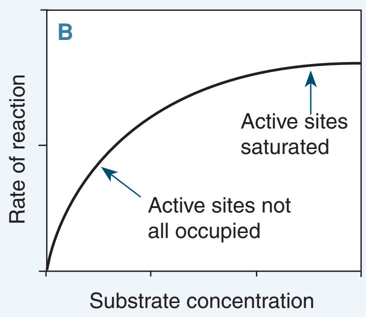
Graph 2



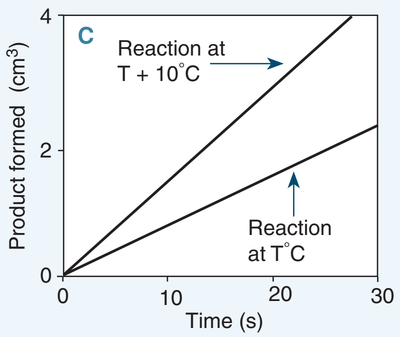
In a reaction in which the rate varies (graph 2) a reaction rate can be calculated for any instantaneous moment in time by using a tangent. The tangent must touch the curve at only one point. The gradient of the tangent can then be used to calculate the rate of reaction at that point in time (A'-B'/D'-C').



Given an unlimited amount of substrate, the rate of reaction will continue to increase as enzyme concentration increases. More enzyme means more reactions between substrates can be catalysed in any given time (graph A).



If there is unlimited substrate but the enzyme is limited, the reaction rate will increase until the enzyme is saturated, at which point the rate will remain static (graph B).



The effect of temperature on a reaction rate is expressed as the temperature coefficient, usually given as the Q_{10}. Q_{10} expresses the increase in the rate of reaction for every rise of 10°C. **Q_{10} = rate of reaction at (T + 10°C)/ rate of reaction at T**, where T is the temperature in °C (graph C).

1. Calculate the reaction rate in graph 1: ______________________

2. For graph 2:

   (a) The reaction rate at 90 seconds: ______________________

   (b) The reaction rate at 30 seconds: ______________________

3. (a) What must be happening to the reaction mix in graph 1 to produce the straight line (constant reaction rate)?

   ____

   ____

   (b) Explain why the reaction rate in graph 2 changes over time: ______________________

   ____

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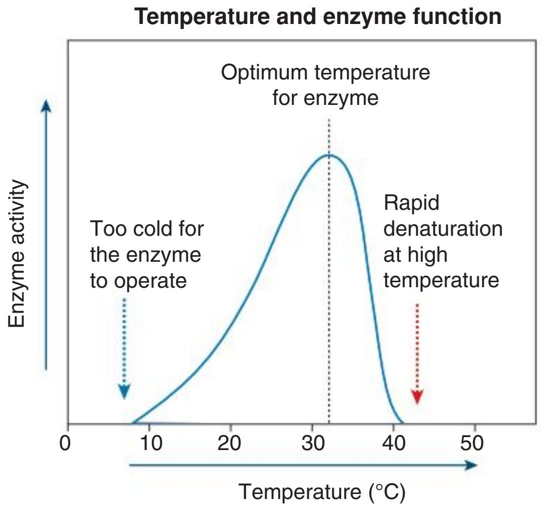
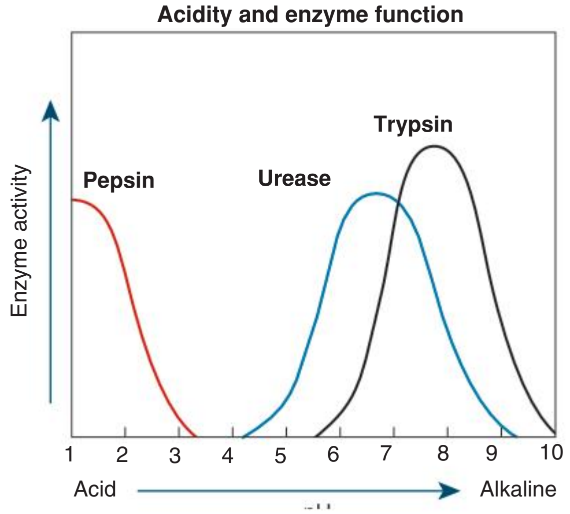


Higher temperatures speed up all reactions, but few enzymes can tolerate temperatures higher than 50–60°C. The rate at which enzymes are **denatured** (change their shape and become inactive) increases with higher temperatures. The temperature at which an enzyme works at its maximum rate is called the **optimum temperature**.



Like all proteins, enzymes are **denatured** by extremes of pH. Within these extremes, most enzymes have a specific pH range for optimum activity. For example, digestive enzymes are specific to the region of the gut where they act: pepsin in the acid of the stomach and trypsin in the alkaline small intestine. Urease catalyses the hydrolysis of urea at a pH near neutral.

4. (a) Describe the change in reaction rate when the enzyme concentration is increased and the substrate is not limiting:

(b) Suggest how a cell may vary the amount of enzyme present:

5. Describe the change in reaction rate when the substrate concentration is increased (with a fixed amount of enzyme):

6. (a) Describe what is meant by an optimum temperature for enzyme activity:

(b) Explain why most enzymes perform poorly at low temperatures:

(c) For graph C on the previous page, calculate the Q_{10} for the reaction:

7. (a) State the optimum pH for each of the enzymes:

Pepsin: ____________ Trypsin: ____________ Urease: ____________

(b) Explain how the pH optima of each of these enzymes is suited to its working environment:

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66 Enzyme Inhibition

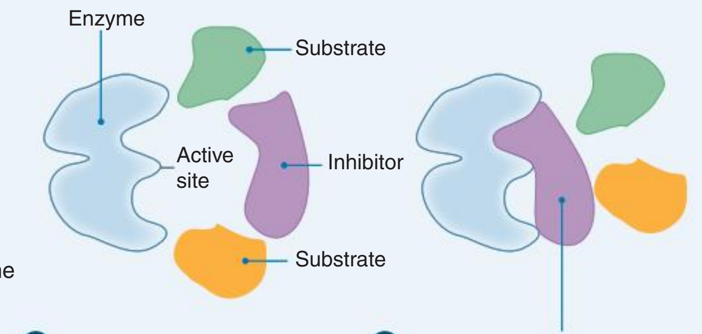
Key Idea: Enzyme activity can be reduced or stopped by inhibitors. These may be competitive or non-competitive.

Enzyme activity can be stopped, temporarily or permanently, by chemicals called enzyme inhibitors. Competitive inhibitors compete directly with the substrate for the active site and their effect can be overcome by increasing the concentration of available substrate. A non-competitive inhibitor does not occupy the active site, but distorts it so that the substrate and enzyme can no longer interact.

Competitive inhibition

Competitive inhibitors compete with the normal substrate for the enzyme's active site.

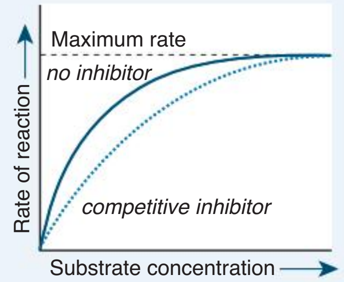
Competitive inhibitors compete directly with the substrate for the active site, and their effect can be overcome by increasing the substrate concentration.



1 Inhibitor is present in the cell (or solution) with the substrate

2 Inhibitor temporarily binds to the active site, blocking it so that the substrate cannot bind

Fig.1 Effect of competitive inhibition on enzyme reaction rate at different substrate concentration

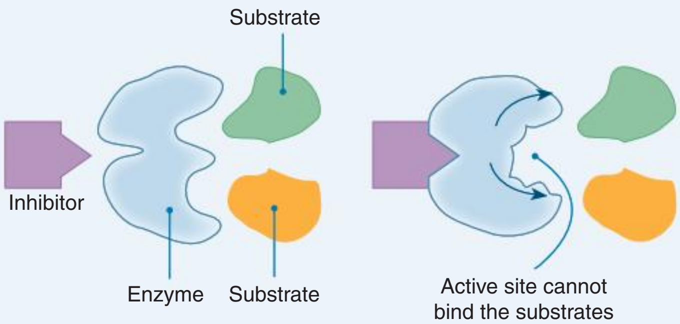


Non-competitive inhibition

Non-competitive inhibitors bind with the enzyme at a site other than the active site.

They inactivate the enzyme by altering its shape so that the substrate and enzyme can no longer interact.

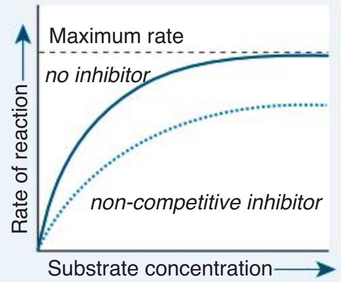
Non-competitive inhibition cannot be overcome by increasing the substrate concentration.



1 Without the inhibitor bound, the enzyme can bind the substrate

2 When the inhibitor binds, the enzyme changes shape.

Fig.2 Effect of non-competitive inhibition on enzyme reaction rate at different substrate concentration



1. Distinguish between competitive and non-competitive inhibition: ______________________

____

____

____

2. (a) Compare and contrast the effect of competitive and non-competitive inhibition on the relationship between the substrate concentration and the rate of an enzyme controlled reaction (figures 1 and 2 above):

____

____

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____

(b) Suggest how you could distinguish between competitive and non-competitive inhibition in an isolated system:

____

____

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67 Investigating Enzyme Activity

Key Idea: The factors affecting peroxidase activity can be measured using the indicator guaiacol.

Enzymes control all the metabolic activities required to sustain life. Changes to environmental conditions (e.g. pH or temperature) may alter an enzyme's shape and functionality. This may result in decreased activity or complete loss of activity if the enzyme is denatured. In this activity you will use the information provided and your own understanding of enzymes to design an experiment to investigate factors affecting enzyme activity.

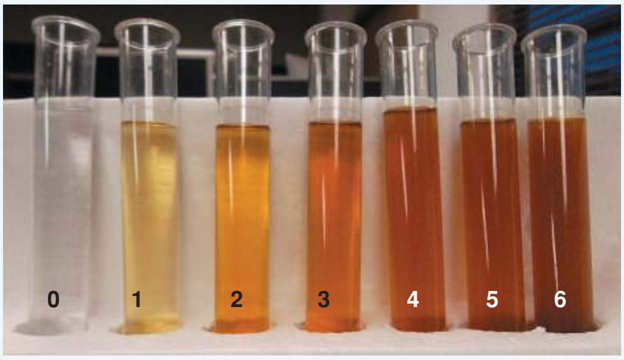
Background

Hydrogen peroxide (H_2O_2) is a toxic by-product of respiration and must be broken down in order to avoid cellular damage. **Peroxidase** acts in the presence of naturally occurring organic reducing agents (electron donors) to catalyse the breakdown of H_2O_2 into water and oxidised organic substrates.

$$2H_2O_2 + 2AH_2 \xrightarrow{\textit{Peroxidase}} 4H_2O + A_2$$

Like all enzymes, the activity of peroxidase is highest within specific ranges of pH and temperature, and activity drops off or is halted altogether when the conditions fall outside of the optimal range. The conversion of H_2O_2 is also influenced by other factors such as the levels of substrate and enzyme.

The effect of peroxidase on H_2O_2 breakdown can be studied using a common reducing agent called guaiacol. Oxidation of guaiacol (as in the equation above) forms tetraguaiacol, which is a dark orange colour. The rate of the reaction can be followed by measuring the intensity of the orange colour as a function of time.



Increasing levels of oxygen production over time (minutes)

A time-colour palette is shown above. You can use it as a reference against which to compare your own results. The palette was produced by adding a set amount of peroxidase to a solution containing hydrogen peroxide and water. The colour change was recorded at set time points (0-6 minutes).

Determining the effect of pH on peroxidase activity

Students examined the effect of pH on peroxidase activity using the following procedure:

- **Substrate tubes** were prepared by adding 7 mL of distilled water, 0.3 mL of 0.1% H_2O_2 solution, and 0.2 mL of prepared guaiacol solution into 6 clean test tubes. The tubes were covered with parafilm and mixed.
- **Enzyme tubes** were prepared by adding 6.0 mL of prepared buffered pH solution (pH 3, 5, 6, 7, 8, 10) and 1.5 mL of prepared turnip peroxidase solution into 6 clean test tubes. The tubes were covered with parafilm and mixed.
- The substrate and enzyme tubes were combined, covered in parafilm, mixed and placed back into a test tube rack at room temperature. Timing began immediately. Students took photos with their phones to record the colour change (relative to the reference colour palette) every minute from time 0-6 minutes. Results are provided in Table 1.

Table 1. Effect of pH on peroxidase activity

	Colour reference number					
	0 min	1 min	2 min	3 min	4 min	5 min
pH 3	0	2	2	3	3	3
pH 5	0	2	4	5	6	6
pH 6	0	3	3	3	3	3
pH 7	0	3	4	4	4	4
pH 8	0	3	3	3	3	3
pH 10	0	0	0	0	0	0

1. Graph the students' results on the grid (right).

2. (a) Describe the effect of pH on peroxidase activity:

4 65

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(b) No colour change was recorded at pH 10. Explain why and relate this finding to the enzyme's structure and the way it interacts with its substrate:

3. The colour palette (opposite) shows the relative amounts of tetraguaiacol formed when guaiacol is oxidised. How can this be used to determine enzyme activity?

4. In the pH experiment, the students measured the rate of enzyme activity by comparing their results against a colour palette. How could they have measured the results quantitatively?

5. How might the results be affected if the students did not begin timing immediately after mixing the enzyme and substrate tubes together?

6. Why is peroxidase written above the arrow in the equation for enzymatic breakdown of H_2O_2?

7. Based on the information provided and your answer to question 4, design an experiment to investigate the effect of lead nitrate (an enzyme inhibitor) on the activity of turnip peroxidase. Summarise your method as step by step instructions below. Note how you will record and display the data and calculate the reaction rate. Include reference to any limitations or sources of potential error in your design:

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68 Achieving Metabolic Efficiency

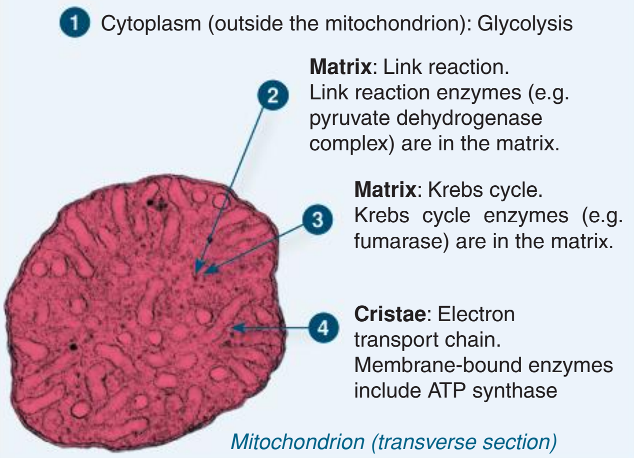
Key Idea: Metabolic pathways are linked biochemical reactions that occur within organisms to maintain life.

Metabolic reactions often occur in as a linked series in which each step in the pathway relies on the completion of a previous step and each step is controlled by specific enzymes. The end product of one enzyme-controlled step provides the substrate for the next step, so failure of one step causes failure of all later steps. Metabolic pathways are tightly controlled to prevent energy being wasted. This energy conservation is termed metabolic efficiency. Metabolic reactions are often localised within specific organelles so that all the components of the pathway are kept together.

Cellular compartments assist efficiency

To increase metabolic efficiency, regions within a cell or an organelle are **compartmentalised** (separated) by membranes. Particular metabolic reactions are restricted to certain regions where all the necessary metabolic components are located. Having compartments within the cell and within organelles prevents interference between different reaction pathways and enables radically different reaction environments to be accommodated within different organelles.

Example: cellular respiration in the mitochondrion
The membrane system of the mitochondrion divides it into several regions. Glycolysis takes place outside of the mitochondrion, in the cell's cytoplasm, but the remaining steps take place in different specialised regions of the mitochondrion. This helps to regulate movement of substrates and end-products and therefore reaction rates, increasing efficiency of the process (below).



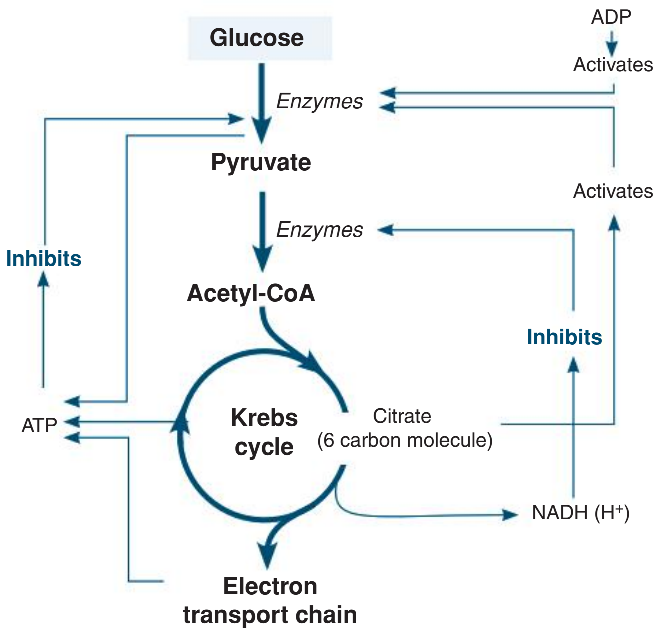
Mitochondrion (transverse section)

WMU

Achieving efficiency by inhibition

Many metabolic pathways are controlled by **feedback inhibition** (negative feedback loop). The pathway is stopped when there is a build-up of end product (or certain intermediate products). The build-up stops the enzymes in the pathway from working and allows the cell to shut down a pathway when it is not needed. This conserves the cell's energy, so it is not manufacturing products it does not need.

Both linear pathways (e.g. glycolysis), and cyclic pathways (e.g. the Krebs cycle) and can be regulated this way (below).



1. What does metabolic efficiency mean? ______________________________

____

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2. Describe how cells achieve metabolic efficiency through:

(a) Compartmentalising: ______________________________

____

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(b) Feedback inhibition: ______________________________

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3. What would happen if cells could not regulate their metabolic pathways? ______________________________

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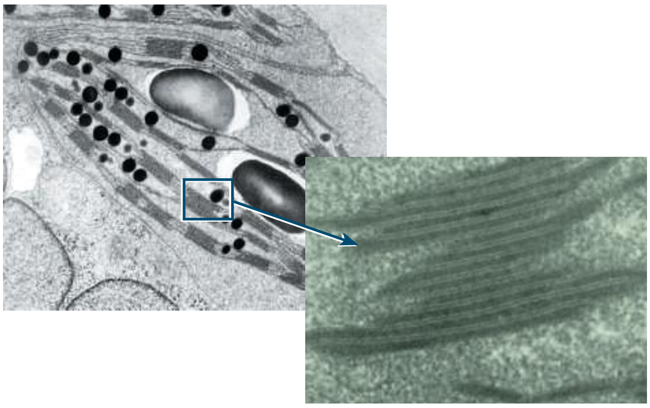
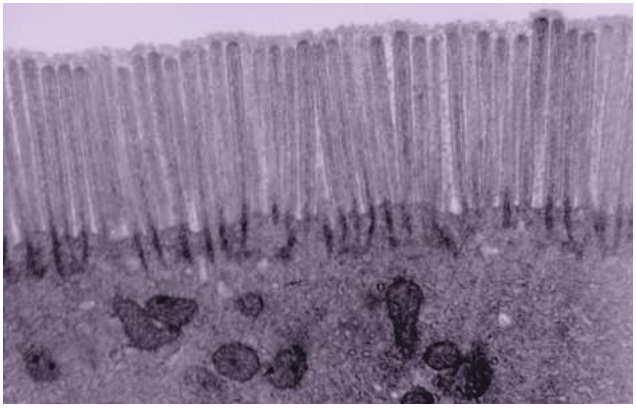
69 Enzymes and Membranes

Key Idea: Increasing the surface area for enzyme attachment increases the number of enzymes that can be present and so also increases the rate of biochemical reactions.

Chemical reactions in organisms must occur at a relatively fast rate. Too slow and the products produced will never be available in the quantities needed to maintain life. One way to increase reaction rate is to concentrate certain enzymes in areas where their substrates are also concentrated. Another way is to increase the surface area for attachment of enzymes so that the number of reactions occurring over any amount of time can be increased. This occurs in many membranous organelles and also in the gut microvilli.



Chloroplasts have internal membranes (thylakoid membranes) organised into stacks called grana. Embedded into the membranes are the protein complexes that capture light and catalyse the light dependent reactions of photosynthesis. The large surface area provided by the thylakoid membranes increases the membrane area for protein attachment and thus the amount of light captured. It also increases the area for associated enzymes that use the captured light to move protons across the membrane and generate ATP.



Intestinal epithelial cells are found lining the villi of the intestinal wall. The cell surface projecting out to the intestinal lumen (space) is covered with microvilli (projections of the plasma membrane). These increase the surface area for absorbing molecules from food in the lumen and increase the surface area for attachment of enzymes that carry out the final stages of carbohydrate digestion. There are also transporter proteins embedded in the membrane. These transport the products of this digestion into the cell.

The enzymes of the electron transport chain in **cellular respiration** are embedded in the internal membranes of the mitochondria. The internal membrane is folded into structures called cristae. These increase the surface area for enzyme attachment and allow a much greater reaction rate.

The **endoplasmic reticulum** is a large region of folded membrane that is attached to the nuclear membrane. Numerous types of enzymes are embedded in the membranes of this organelle, including ribosomes, which catalyse protein synthesis (on the rough endoplasmic reticulum).

1. How do cells increase cellular membrane surface area? ______

2. (a) How does increasing surface area of cellular membranes help to increase reaction rates in cells?

______

(b) Why is increasing the reaction rate important in cells? ______

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70 KEY TERMS AND IDEAS: Did You Get It?

1. Test your vocabulary by matching each term to its correct definition, as identified by its preceding letter code.

- activation energy ....
- active site ....
- anabolic reactions ....
- catabolic reactions ....
- catalyst ....
- denaturation ....
- enzymes ....
- induced fit model ....

A The energy that must be overcome in order for a chemical reaction to occur.

B Any reagent that increases the rate of a chemical reaction but is itself not consumed by the reaction.

C The region of an enzyme responsible for substrate binding and reaction catalysis.

D Reactions that build larger molecules from smaller ones.

E Biological catalysts, usually globular proteins.

F The currently accepted model for enzyme function.

G Reactions that break up larger molecules into their component parts.

H The loss of a protein's three dimensional functional structure is called this.

2. Study the enzymatic word equation below and answer the following questions:

$$\text{Sucrose + Water} \xrightarrow{\textit{Sucrase}} \text{Glucose + Fructose}$$

(a) Identify the substrate: ______________________

(b) Identify the products: ______________________

(c) Identify the enzyme: ______________________

3. Some heavy metals act as irreversible competitive inhibitors. Why does this make them dangerous poisons?

____

____

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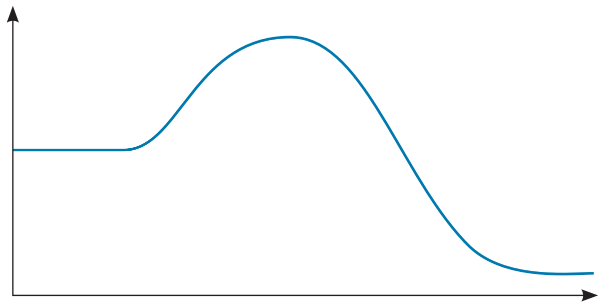
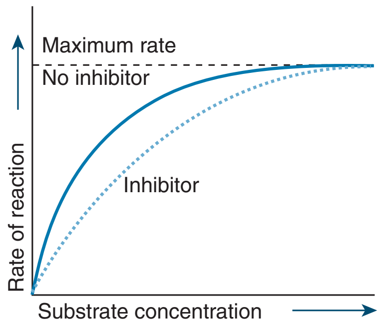
4. (a) Label the graph right with axes and the following labels: Reactants, products, activation energy, transition state.

(b) Assume the reaction has had no enzyme added. Draw the shape of the graph when an enzyme is added to the reaction mix.



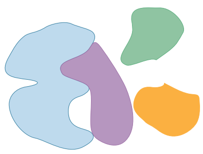
5. The graph (right) shows the effect of an enzyme inhibitor in enzyme reaction rate.



(a) It shows competitive inhibition/non-competitive inhibition (delete one).

(b) Identify the diagram below that illustrates your choice in (a): ______________

A



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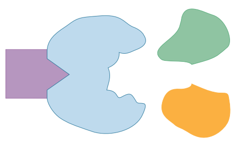

6. Identify two ways organelles can increase the rate and efficiency of metabolic reactions:

____

____

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UNIT 1
Topic 1

Energy and Metabolism

Key terms

aerobic
alcoholic fermentation
anaerobic
ATP
autotrophic
Calvin cycle
carbohydrate
cellular respiration
chlorophyll
chloroplast
cristae
electron transport chain
ethanol
fermentation
glycolysis
grana
heterotrophic
Krebs cycle
lactic acid fermentation
light dependent reactions
light independent reactions
matrix
mitochondrion
photosynthesis
stroma
thylakoids

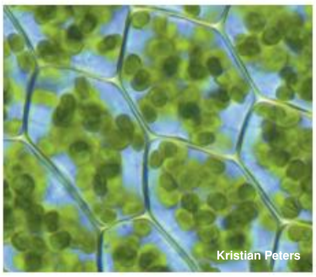
Activity number

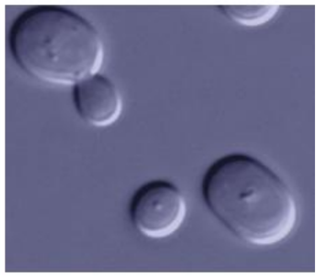
Obtaining energy for life

Key skills and knowledge

☐ 1 Explain the role of ATP (adenosine triphosphate) as an energy carrier in cells. Recall that organisms obtain the energy they need to recycle ATP from glucose molecules through the process of cellular respiration. Contrast the source of this glucose in autotrophs and heterotrophs. **71 77**

☐ 2 Compare cellular respiration and photosynthesis as energy transformation processes. Include reference to the relationship between the raw materials and products of the processes. Analyse diagrams and schematics of energy transfer. **71 79-81**





Photosynthesis

Key skills and knowledge

☐ 3 Describe the ecological role and importance of plants as producers. Recall that photosynthesis is an enzyme-controlled series of chemical reactions occurring in the chloroplasts of plant cells and it uses light energy to synthesis glucose. **72**

☐ 4 Summarise photosynthesis in both a word equation and a balanced chemical equation, identifying raw materials and end products. Identify the form in which the food is produced and what it is used for. Summarise photosynthesis in terms of the light dependent reactions and the light independent reactions (the Calvin cycle). **74**

☐ 5 Describe features of chloroplasts that are related to their role in photosynthesis. **73**

☐ 6 PRAC Investigate the effect of light on the outputs of photosynthesis. **75**

☐ 7 SHE Describe how enhancing photosynthesis could improve production of food and fuel, reduce dependence on fossil fuels, and improve sustainability. **76**

Cellular respiration

Key skills and knowledge

☐ 8 Explain why organisms need to respire, recalling the universal role of ATP in metabolism. Recognise that organisms can respire aerobically and anaerobically. **77**

☐ 9 Recognise that cellular respiration is an enzyme-controlled series of chemical reactions and that aerobic respiration requires oxygen. **79**

☐ 10 Recall the structure of a mitochondrion and its role in cellular respiration. Identify the main steps in the complete oxidation of glucose by aerobic cellular respiration: glycolysis, Krebs cycle, and electron transport chain. **79**

☐ 11 Summarise the reactions of aerobic respiration in a word equation and in a chemical equation, including the ATP yield. Teacher's note: The actual ATP yield is lower than the theoretical maximum yield of 36-38 ATP because of factors (such as membrane leakiness) that dissipate the proton gradient and reduce efficiency. **79**

☐ 12 Describe anaerobic (without oxygen) pathways for ATP generation in eukaryotes: lactic acid fermentation in mammalian muscle and alcoholic fermentation in yeast and plant roots. Compare the energy yield from aerobic and anaerobic pathways. Teacher's note: Fermentation is not the same as anaerobic respiration, which, by definition, involves an electron transport chain with an electron acceptor other than oxygen, e.g. nitrate, sulfate, or elemental sulfur. Fermentation utilises substrate-level phosphorylation and not an electrochemical gradient to generate ATP. **81**

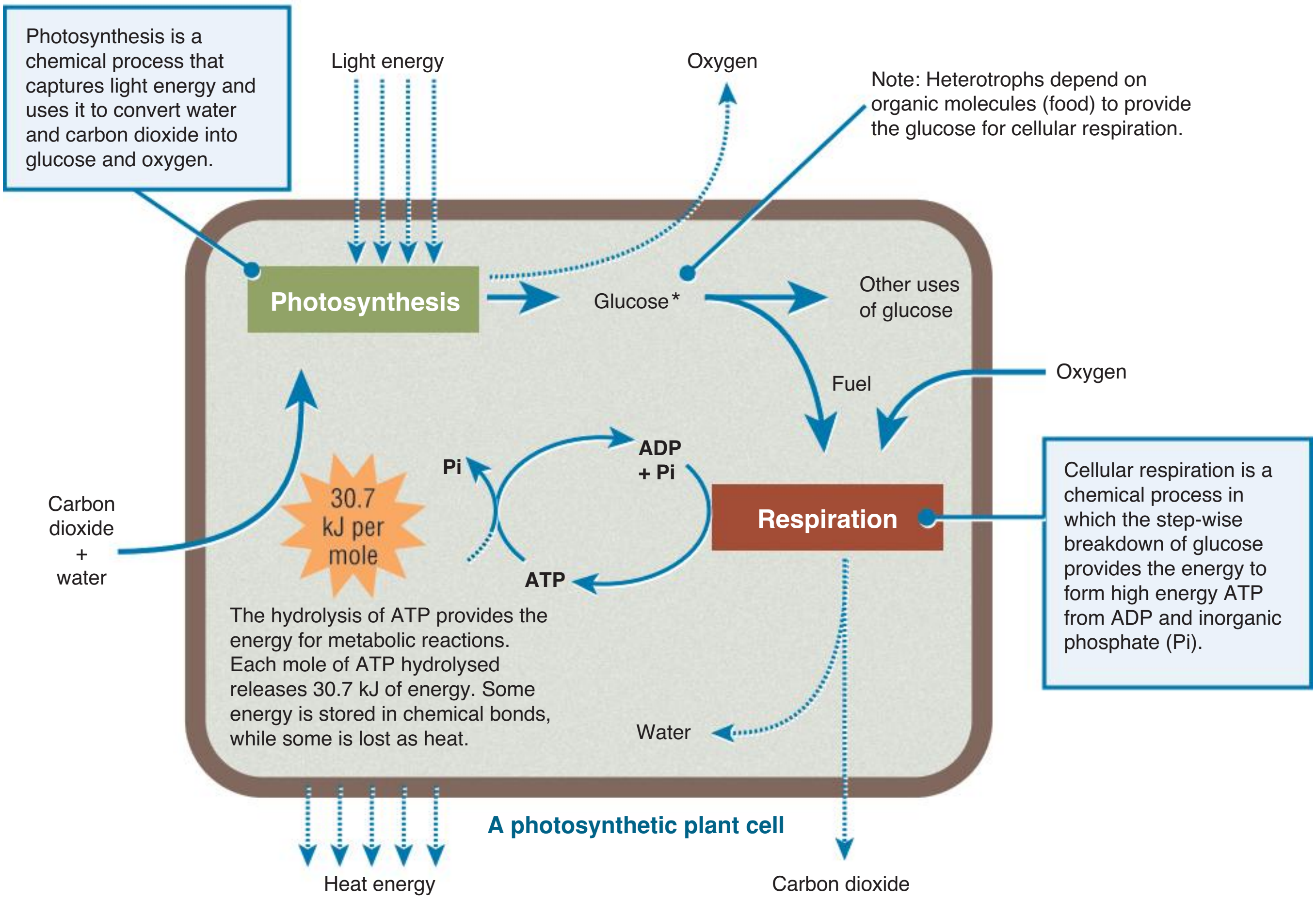
☐ 13 PRAC Measure oxygen consumption in respiring organisms using a respirometer. **78**

☐ 14 PRAC Measure the outputs of fermentation in yeast grown on different substrates. **82**

71 Energy Transformations in Cells

Key Idea: The energy from sunlight is captured and stored as glucose, which powers the production of ATP in the process of cellular respiration. Hydrolysis of ATP provides the energy for the chemical reactions in living systems.

Energy flow in the cell of an autotroph (a plant) is shown below. Note that ATP has a central role in acting as an energy carrier to power metabolic reactions. Some of the energy is lost as heat during these reactions.



DID YOU KNOW?

It takes energy to break bonds, so how does the hydrolysis of ATP provide energy for metabolic reactions?
The hydrolysis of ATP is linked to the formation of a reactive intermediate, which can be used to do work. The reactions that make the energy in ATP available occur virtually simultaneously, so the reaction is simplified to omit the intermediates:

$$\text{A + B} \longrightarrow \text{AB + heat energy}$$
$$\text{ATP} \longrightarrow \text{ADP + Pi}$$

1. How does ATP act as a supplier of energy to power metabolic reactions? ______________________

____

____

2. (a) Identify the ultimate source of energy for most autotrophs: ______________________

(b) Identify a group of autotrophic organisms that do not use this source of energy: ______________________

____

3. Identify the ultimate source of energy for most heterotrophs: ______________________

4. In what way are the processes pictured above (photosynthesis and cellular respiration) connected? ______________________

____

____

____

ISBN: 978-1-927309-83-4

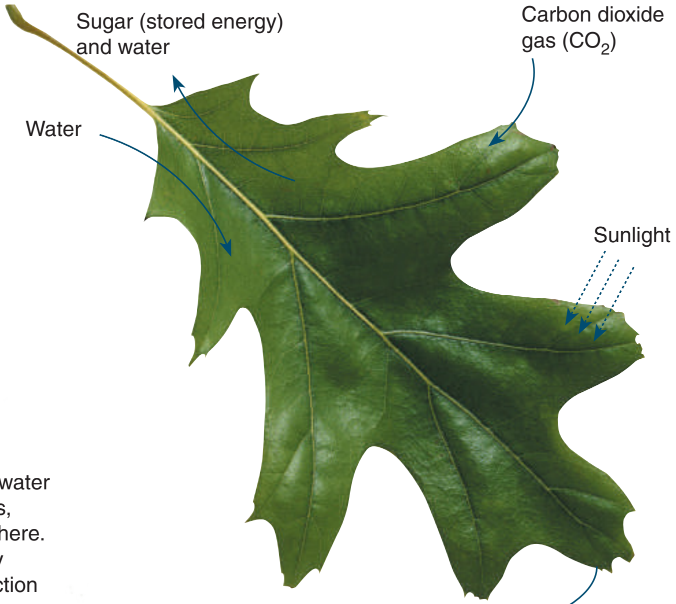
72 The Role of Photosynthesis

Key Idea: Photosynthesis is the chemical process in which autotrophs use sunlight to produce carbohydrates.

Photosynthesis is the process by which plants capture light energy and use it to fix (convert) the carbon in CO_2 into carbohydrates (e.g. glucose). The carbohydrate is used by the plant to power ATP production and build its body. Plants (and other photosynthetic organisms) carry out this process without input from other organisms, so they are called **producers** (as opposed to consumers, which depend on energy and carbon from other organisms).

Photosynthesis and producers

- A **producer** (or autotroph) is an organism that can make its own food.
- Plants, algae, and some bacteria are producers.
- Most producers use the energy in sunlight to make their food. The process by which they do this is called **photosynthesis**. Photosynthesis transforms sunlight energy into chemical energy.
- The chemical energy is stored as glucose, and the energy is released when the glucose undergoes further metabolic processes.
- The inputs and outputs of photosynthesis are shown on the leaf diagram (right).



DID YOU KNOW?

The evolution of oxygenic photosynthesis, in which water is split to provide the hydrogens to drive the process, was responsible for our current oxygen rich atmosphere. Using water (rather than hydrogen sulfide) to supply hydrogens provided far more energy for ATP production and produced oxygen gas as a waste product.

Photosynthesis by marine algae provides oxygen and absorbs carbon dioxide. Most algae are microscopic but some, like this kelp, are large.

Depending on the plant, 0.1% to 8% of the light intercepted is used in photosynthesis. Typically crop plants use about 1%-2%.

Producers, such as grasses, make their own food, and are also the ultimate source of food and energy for consumers, such as this cow.

1. (a) What is a producer? ______________________________

   ____

   (b) Name some organisms that are producers: ______________________________

   ____

2. Where do producers get their energy from? ______________________________

   ____

3. Why are producers so important in an ecosystem? ______________________________

   ____

   ____

   ____

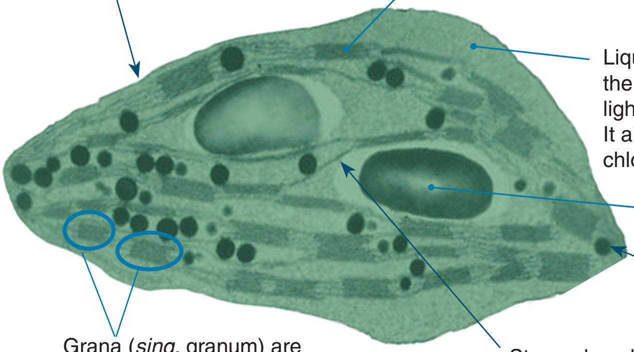
ISBN: 978-1-927309-83-4

73 Chloroplasts

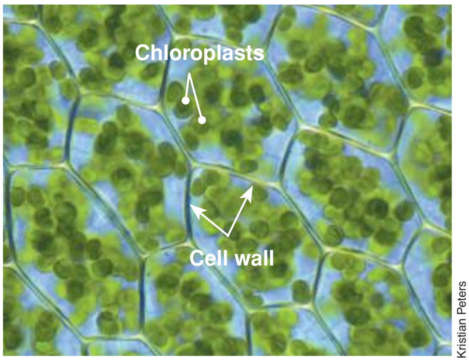
Key Idea: Chloroplasts have a complicated internal membrane structure. They are the site of photosynthesis in plant cells.

Chloroplasts are the specialised plastids in which photosynthesis occurs. A mesophyll (photosynthetic) leaf cell contains between 50-100 chloroplasts. The chloroplasts are generally aligned so that their broad surface runs parallel to the cell wall to maximise the surface area available for light absorption. Chloroplasts have an internal structure characterised by a system of membranous structures called thylakoids arranged into stacks called grana. Special pigments, called chlorophylls and carotenoids, are bound to the membranes as part of light-capturing photosystems. They absorb light of specific wavelengths and thereby capture the light energy.

The structure of a chloroplast



TEM image of a single chloroplast



Chloroplasts visible in plant cells

1. Label the transmission electron microscope image of a chloroplast below:

(a) ____________

(b) ____________

(c) ____________

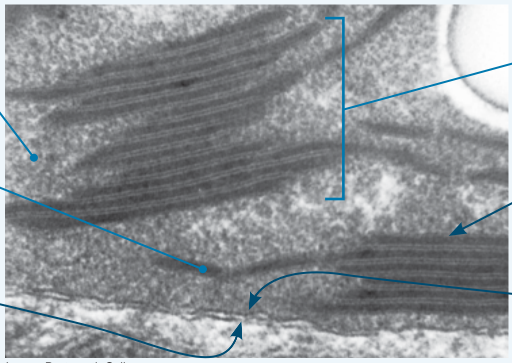


Image: Dartmouth College

(d) ____________

(e) ____________

(f) ____________

2. (a) Where is chlorophyll found in a chloroplast? ____

(b) Why is chlorophyll found there? ____

3. Explain how the internal structure of chloroplasts helps absorb the maximum amount of light: ____

4. Explain why plant leaves appear green: ____

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74 Photosynthesis: Inputs and Outputs

Key Idea: Photosynthesis is the process by which light energy is used to convert CO_2 and water into glucose and oxygen.

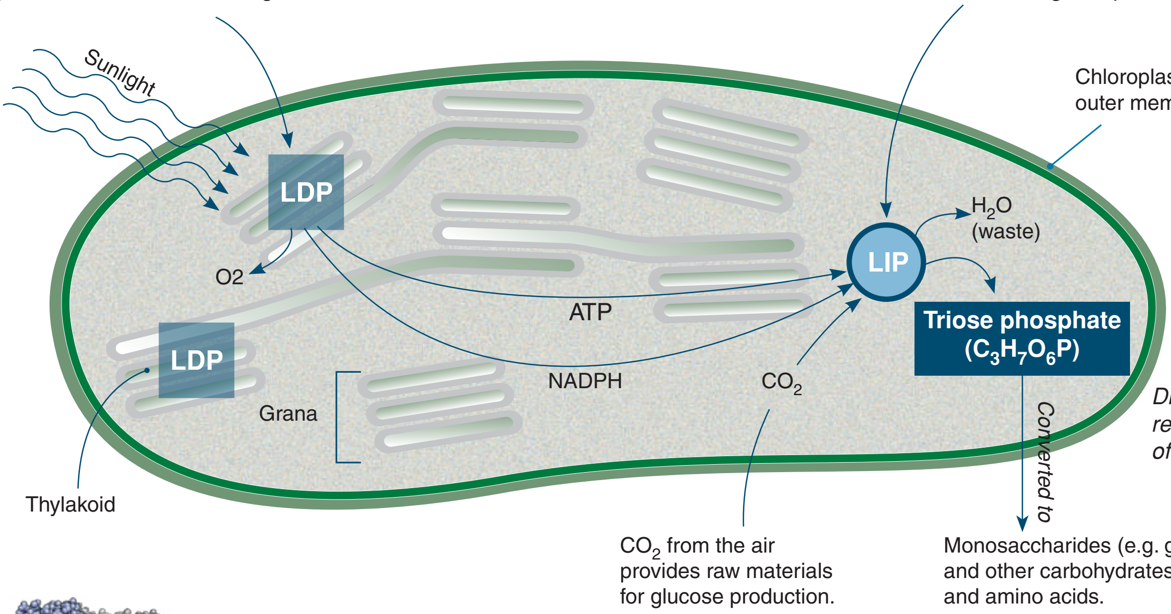
Photosynthesis is of fundamental importance to living things because it transforms sunlight energy into chemical energy stored in molecules, releases free oxygen gas, and absorbs carbon dioxide (a waste product of cellular metabolism). Photosynthesis has two phases, the light dependent phase and the light independent phase. In the reactions of the light dependent phase, light energy is converted to chemical energy (ATP and NADPH). This phase occurs in the thylakoid membranes of the chloroplasts. In the reactions of the light independent phase, the chemical energy is used to synthesise carbohydrate. This phase occurs in the stroma of chloroplasts. In photosynthesis, water is split and electrons are transferred together with hydrogen ions from water to CO_2, reducing it to triose phosphates (then converted to sugars).

Light dependent phase (LDP):

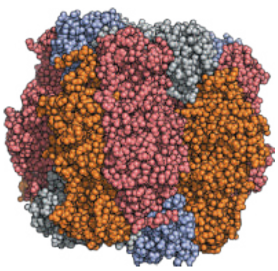
In the first phase of photosynthesis, chlorophyll captures light energy, which is used to split water, producing O_2 gas (waste). Electrons and H^+ ions are transferred to the molecule NADPH. ATP is also produced. The light dependent phase occurs in the thylakoid membranes of the grana.

Light independent phase (LIP):

The second phase of photosynthesis occurs in the stroma and uses the NADPH and the ATP to drive a series of enzyme-controlled reactions (the **Calvin cycle**) that fix carbon dioxide to produce triose phosphate. This process, called **carbon fixation**, does not need light to proceed.



Diagrammatic representation of a chloroplast



Rubisco (left) is the central enzyme in the LIP of photosynthesis (carbon fixation) catalysing the first step in the Calvin cycle.

The general equation for photosynthesis

$$6CO_2 + 6H_2O \xrightarrow[\text{Chlorophyll}]{\text{Light}} C_6H_{12}O_6 + 6O_2$$

1. Explain how the light-dependent reaction and the light independent reaction are linked: ______________________

____

____

____

2. Write a word equation for photosynthesis: ______________________

3. What is Rubisco and what is its role? ______________________

____

4. State the fate of the following molecules involved in photosynthesis:

(a) Carbon dioxide: ______________________

(b) Oxygen: ______________________

(c) Hydrogen: ______________________

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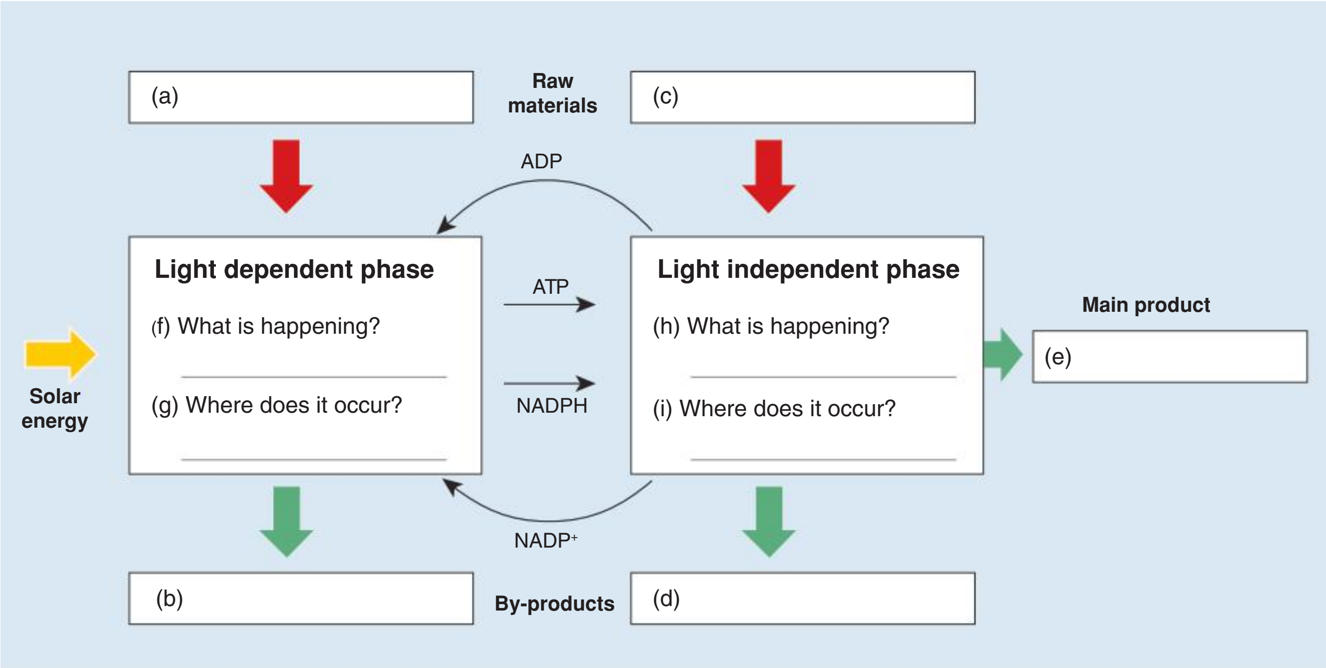
5. Use the information on the previous page to fill in the diagram below. Fill in the raw material (inputs), products (outputs), and state what is happening at each phase and where the phase takes place (occurs).



6. In two experiments, radioactively-labelled oxygen (shown in blue) was used to follow oxygen through the photosynthetic process. The results of the experiment are shown below:

Experiment A: $6CO_2 + 12H_2\mathbf{O}$ + sunlight energy→ $C_6H_{12}O_6 + 6\mathbf{O}_2 + 6H_2O$

Experiment B: $6C\mathbf{O}_2 + 12H_2O$ + sunlight energy→ $C_6H_{12}\mathbf{O}_6 + 6O_2 + 6H_2O$

From these results, what would you conclude about the source of the oxygen in:

(a) The carbohydrate produced? ____________________

(b) The oxygen released? ____________________

7. Name the products that triose phosphate is converted into: ____________________

____

8. Describe what happens during:

(a) The light dependent phase of photosynthesis: ____________________

____

____

(b) The light independent phase of photosynthesis: ____________________

____

____

9. What is the function of each of the following in photosynthesis:

(a) ATP: ____________________

(b) NADPH: ____________________

(c) Light: ____________________

(d) Chlorophyll: ____________________

(e) Carbon dioxide: ____________________

(f) Water: ____________________

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75 Investigating Photosynthetic Rate

Key Idea: Measuring the production of oxygen provides a simple means of measuring the rate of photosynthesis.

The rate of photosynthesis can be investigated by measuring the substances involved in photosynthesis. These include measuring the uptake of carbon dioxide, the production of oxygen, or the change in biomass over time. Measuring the rate of oxygen production provides a good approximation of the photosynthetic rate and is relatively easy to carry out.

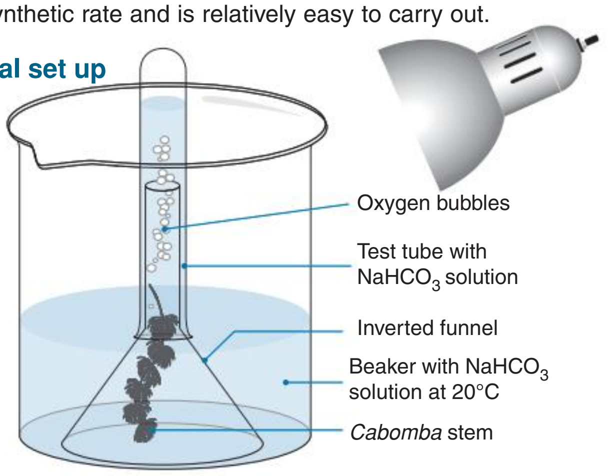
The aim

To investigate the effect of light intensity on the rate of photosynthesis in an aquatic plant, *Cabomba aquatica*.

The method

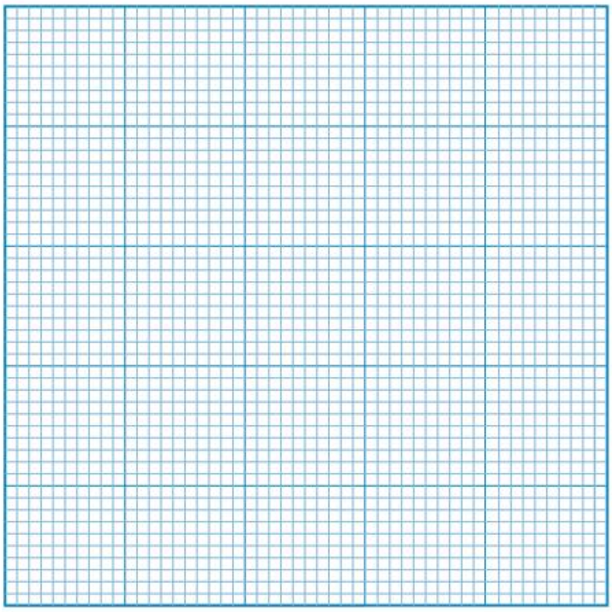
- 0.8-1.0 grams of *Cabomba* stem were weighed on a balance. The stem was cut and inverted to ensure a free flow of oxygen bubbles.
- The stem was placed into a beaker filled with a solution containing 0.2 mol L^{-1} sodium hydrogen carbonate (to supply carbon dioxide). The solution was at approximately 20°C. A funnel was inverted over the *Cabomba* and a test tube filled with the sodium hydrogen carbonate solution was inverted on top to collect any gas produced.
- The beaker was placed at distances (20, 25, 30, 35, 40, 45, 50 cm) from a 60W light source and the light intensity measured with a lux meter at each interval.
- Before recording data, the *Cabomba* stem was left to acclimatise to the new light level for 5 minutes. Because the volumes of oxygen gas produced are very low, bubbles were counted for a period of three minutes at each distance.

Experimental set up



The results

Light intensity (lx) (distance)	Bubbles counted in three minutes	Bubbles per minute
5 (50 cm)	0	
13 (45 cm)	6	
30 (40 cm)	9	
60 (35 cm)	12	
95 (30 cm)	18	
150 (25 cm)	33	
190 (20 cm)	35	



1. Complete the table above by calculating the rate of oxygen production (bubbles of oxygen gas per minute):

2. Use the data to draw a graph of the bubble produced per minute vs light intensity:

3. Although the light source was placed set distances from the *Cabomba* stem, light intensity in lux was recorded at each distance rather than distance *per se*. Explain why this would be more accurate:

4. The sample of gas collected during the experiment was tested with a glowing splint. The splint reignited when placed in the gas. What does this confirm about the gas produced?

5. What could be a more accurate way of measuring the gas produced in the experiment?

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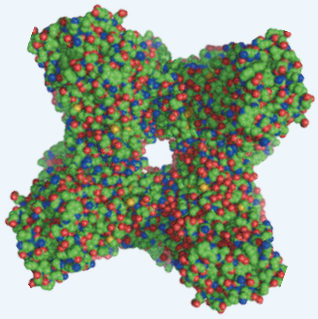
76 Photosynthesis and Productivity

Key Idea: Increasing productivity by improving photosynthetic efficiency could help to increase food and fuel production.

The glucose produced in photosynthesis can be converted into biomass, which can be used for food or fuel (e.g. biodiesel). However, photosynthesis is an inefficient process. Productivity (i.e the rate of biomass production) can be improved by manipulating biotic factors such as light or CO_2 levels and growing plants in a greenhouse. More recently scientists have begun to look at other ways to increase photosynthesis to meet the increasing demand for food and fuel required by our growing population. Many solutions focus around improving Rubisco performance.

Rubisco

- Rubisco enzyme (right) catalyses the first major step in carbon fixation.
- Rubisco activity is very inefficient, processing just three reactions a second.
- This inefficiency makes the first step the rate limiting step of the entire photosynthetic pathway.
- To compensate for its inefficiency, Rubisco is present in high levels within a plant, it makes up almost half the protein content of chloroplasts.



Suggestions for improving productivity

- Improving the catalytic activity of Rubisco.
- Increasing the amount of Rubisco in the leaf.
- Enhancing the CO_2 concentration around Rubisco.
- Improving Rubisco's affinity for CO_2.
- Enhancing chloroplast electron transport rate.
- Increasing the thermostability of Rubisco Activase, an enzyme involved in activating Rubisco.
- Gene insertion from more efficient plants.

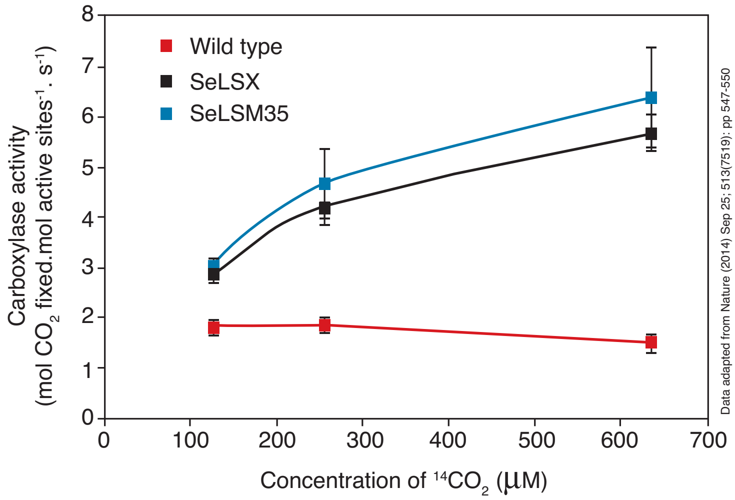
Improving Rubisco activity

Rubisco catalyses two reactions; one is carbon fixation and the other is a reaction with oxygen. This dual processing capability reduces the amount of time it can spend fixing carbon, and so reduces photosynthesis productivity. Researchers have investigated a number of ways to improve productivity, including the genetic modification of Rubisco.

Cyanobacteria have a CO_2 concentrating mechanism (CCM), which allows them to produce a CO_2 rich environment around Rubisco. This improves photosynthetic productivity and there is less oxygen reacting with Rubisco.

Two genes (SeLSX and SeLSM35) from the cyanobacterium *Synechococcus elongatus* PCC7942 were transplanted into the DNA of the chloroplasts of the tobacco plant. The graph on the right shows the carbon fixation results of the two modified tobacco plants compared against the wild type.

Mean carboxylase activity (± standard deviation) as a measure of carbon dioxide fixation in tobacco plants.



1. Why has it become important for researchers to look at ways of boosting photosynthesis productivity? ____________

2. (a) How do cyanobacteria improve their photosynthetic activity? ____________

(b) Describe the effect of the transplanted cyanobacteria genes on Rubisco activity in tobacco plant: ____________

3. In small groups choose a different mechanism for improving photosynthetic efficiency (and therefore productivity) from the list at the top of the page. Research the mechanism and success to date and report your findings to the class.

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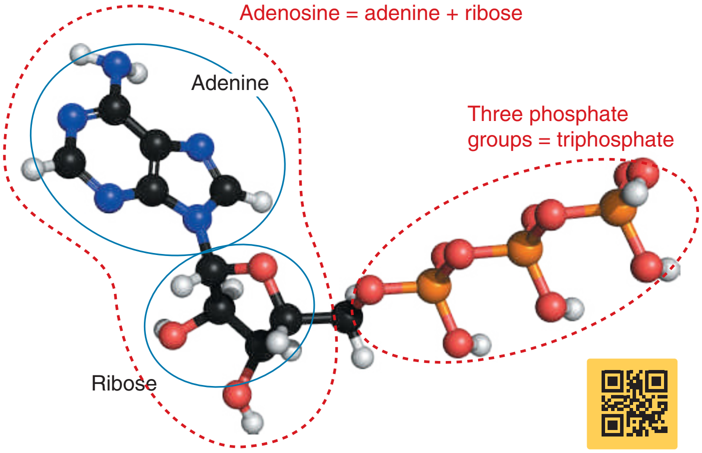
77 ATP in Cells

Key Idea: ATP transports chemical energy within the cell for use in metabolic processes.

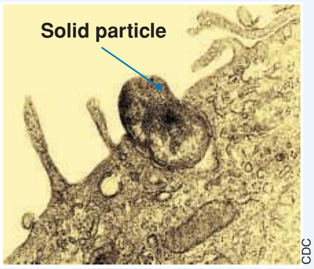
All organisms require energy to be able to perform the metabolic processes required for them to function and reproduce. This energy is obtained by **cellular respiration**, a set of metabolic reactions which ultimately convert biochemical energy from 'food' into the nucleotide **adenosine triphosphate** (ATP). ATP is considered to be a universal energy carrier, transferring chemical energy within the cell for use in metabolic processes such as biosynthesis, cell division, cell signalling, thermoregulation, cell mobility, and active transport of substances across membranes.

Adenosine triphosphate (ATP)

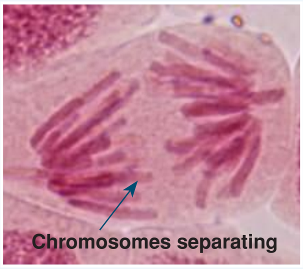
- The ATP molecule consists of three components; a purine base (**adenine**), a pentose sugar (**ribose**), and **three phosphate groups** which attach to the 5' carbon of the pentose sugar. Adenine + ribose form adenosine (the "A" in ATP). The structure of ATP is shown right.
- The bonds between the phosphate groups contain electrons in a high energy state which store a large amount of energy. The energy is released during ATP hydrolysis. Typically, hydrolysis is coupled to another cellular reaction to which the energy is transferred. The end products of the reaction are adenosine diphosphate (ADP) and an inorganic phosphate (Pi).
- Note that energy is released during the formation of bonds during the hydrolysis reaction, not the breaking of bonds between the phosphates (which requires energy input).



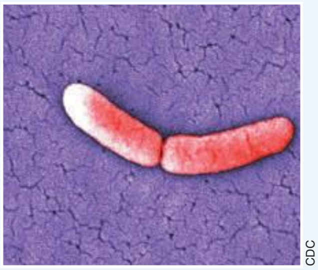
ATP powers metabolism



The energy released from the removal of a phosphate group of ATP is used for active transport of molecules and substances across the plasma membrane e.g. **phagocytosis** (above) and other active transport processes.



Mitosis, as seen in this stained onion cell, requires ATP to proceed. Formation of the mitotic spindle and chromosome separation both require the energy provided by ATP hydrolysis to occur.



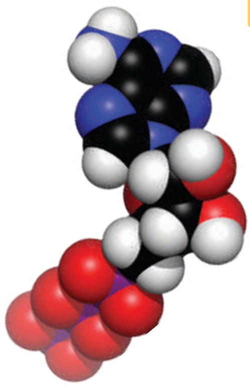
ATP is required when bacteria divide by binary fission (above). For example, ATP is required in DNA replication and to synthesise components of the peptidoglycan cell wall.

Not all of the energy released in the oxidation of glucose is captured in ATP. The rest is lost as heat. This heat energy can be used to maintain body temperature. Thermoregulatory mechanisms such as shivering and sweating also use ATP.

1. What process produces ATP in a cell? ______________________________

____

2. On the space filling model of ATP shown right, label adenine, ribose and the phosphate groups:



3. Explain why thermoregulation requires the expenditure of energy:

____

____

____

____

4. Describe one other process in a cell that requires ATP: ______________________________

____

____

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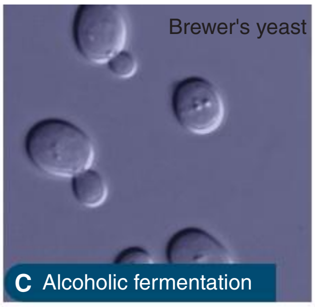
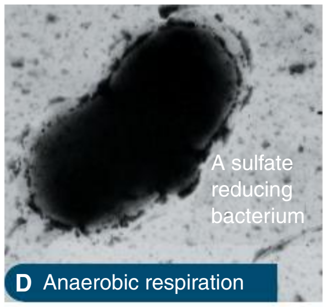
Aerobic and anaerobic pathways for ATP production

A Aerobic respiration

B Lactic acid fermentation



C Alcoholic fermentation



D Anaerobic respiration

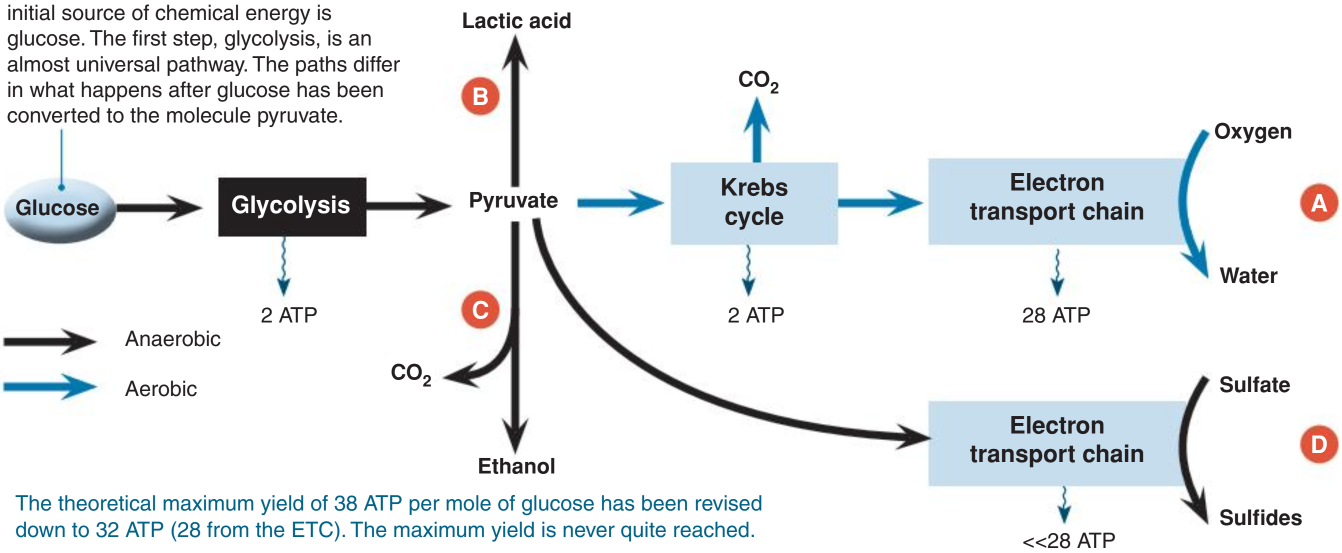
Aerobic respiration produces the energy (as ATP) needed for metabolism. The rate of aerobic respiration is limited by the amount of oxygen available. In animals and plants, most of the time the oxygen supply is sufficient to maintain aerobic metabolism. Aerobic respiration produces a high yield of ATP per molecule of glucose (**path A**).

During maximum physical activity, when oxygen is limited, anaerobic metabolism provides ATP for working muscle. In mammalian muscle, metabolism of a respiratory intermediate produces lactate, which provides fuel for working muscle and produces a low yield of ATP. This process is called lactic acid fermentation (**path B**).

The process of brewing utilises the anaerobic metabolism of yeasts. Brewer's yeasts preferentially use anaerobic metabolism in the presence of excess sugars. This process, called alcoholic fermentation, produces ethanol and CO_2 from the respiratory intermediate pyruvate. It is carried out in vats that prevent entry of O_2 (**path C**)

Many bacteria and archaea are anaerobic, using molecules other than oxygen (e.g. nitrate or sulfate) as a terminal electron acceptor of their electron transport chain. These electron acceptors are not as efficient as oxygen (less energy is released per oxidised molecule) so the energy (ATP) yield from anaerobic respiration is generally quite low (**path D**).

In most energy-yielding pathways the initial source of chemical energy is glucose. The first step, glycolysis, is an almost universal pathway. The paths differ in what happens after glucose has been converted to the molecule pyruvate.



The theoretical maximum yield of 38 ATP per mole of glucose has been revised down to 32 ATP (28 from the ETC). The maximum yield is never quite reached.

5. What do all the ATP yielding pathways above have in common? ____________________

6. Distinguish between anaerobic pathways in eukaryotes (e.g. yeasts) and anaerobic respiration in anaerobic microbes:

7. When brewing alcohol, why is it important to prevent entry of oxygen to the fermentation vats? ____________________

8. Rank the following processes from lowest to highest in terms of ATP produced (use = for processes you consider equal in yield): *lactic acid fermentation, anaerobic respiration, alcoholic fermentation, aerobic respiration, glycolysis*.

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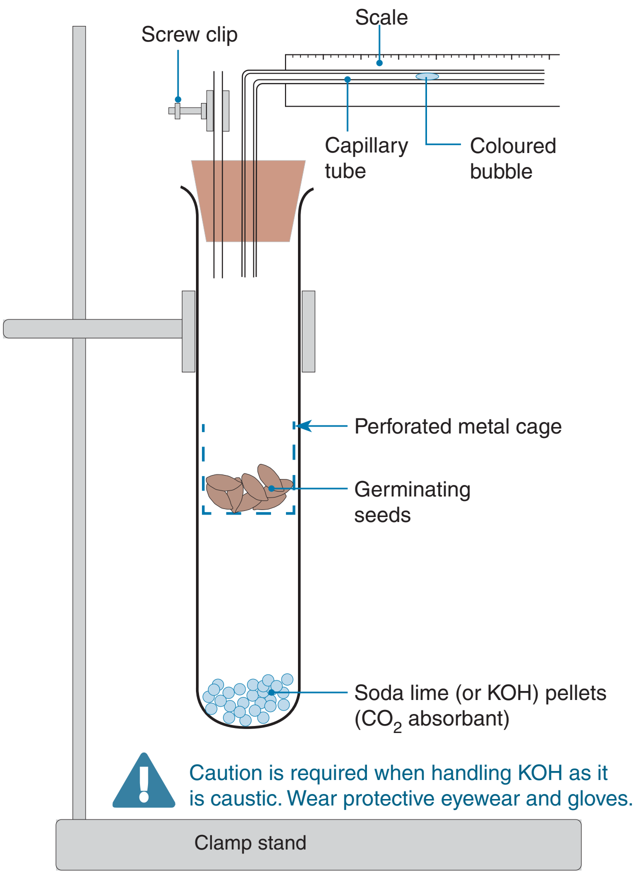
78 Measuring Respiration

Key Idea: Oxygen consumption in respiring organisms can be measured with a respirometer.

A respirometer measures the amount of oxygen consumed during cellular respiration. Respirometers are simple pieces of apparatus but can give accurate results for rate of oxygen consumption if set up carefully.



Measuring respiration with a simple respirometer

The diagram on the left shows a **simple respirometer**. It measures the change in gases as respiration occurs.

- Respiring organisms, in this case germinating seeds, are placed into the bottom of the chamber.
- Soda lime or potassium hydroxide is added to absorb any carbon dioxide produced during respiration. Therefore the respirometer measures oxygen consumption.
- Once the organisms have been placed into the chamber the screw clip is closed. The start position of the coloured bubble is measured (this is the time zero reading).
- The coloured bubble in the capillary tube moves in response to the change in oxygen consumption. Measuring the movement of the liquid (e.g. with a ruler) allows the change in volume of gas to be estimated.
- Care needs to be taken when using a simple respirometer because changes in temperature or atmospheric pressure may change the readings and give a false measure of respiration.
- Differential respirometers (not shown) use two chambers (a control chamber with no organisms and a test chamber) connected by a U-tube. Changes in temperature or atmospheric pressure act equally on both chambers. Observed changes are only due to the activities of the respiring organism.

1. Why does the bubble in the capillary tube move?

___

___

___

2. A student used a simple respirometer (like the one above) to measure respiration in maggots. Their results are presented in the table (right). The maggots were left to acclimatise for 10 minutes before the experiment was started.

(a) Calculate the rate of respiration and record this in the table. The first two calculations have been done for you.

(b) Plot the rate of respiration on the grid, below right.

(c) Describe the results in your plot: ___

___

___

___

___

Time (minutes)	Distance bubble moved (mm)	Rate (mm min^{-1})
0	0	–
5	25	5
10	65	
15	95	
20	130	
25	160	

(d) Why was there an acclimatisation period before the experiment began?

___

___

3. Why would it have been better to use a differential respirometer? ___

___

___

___

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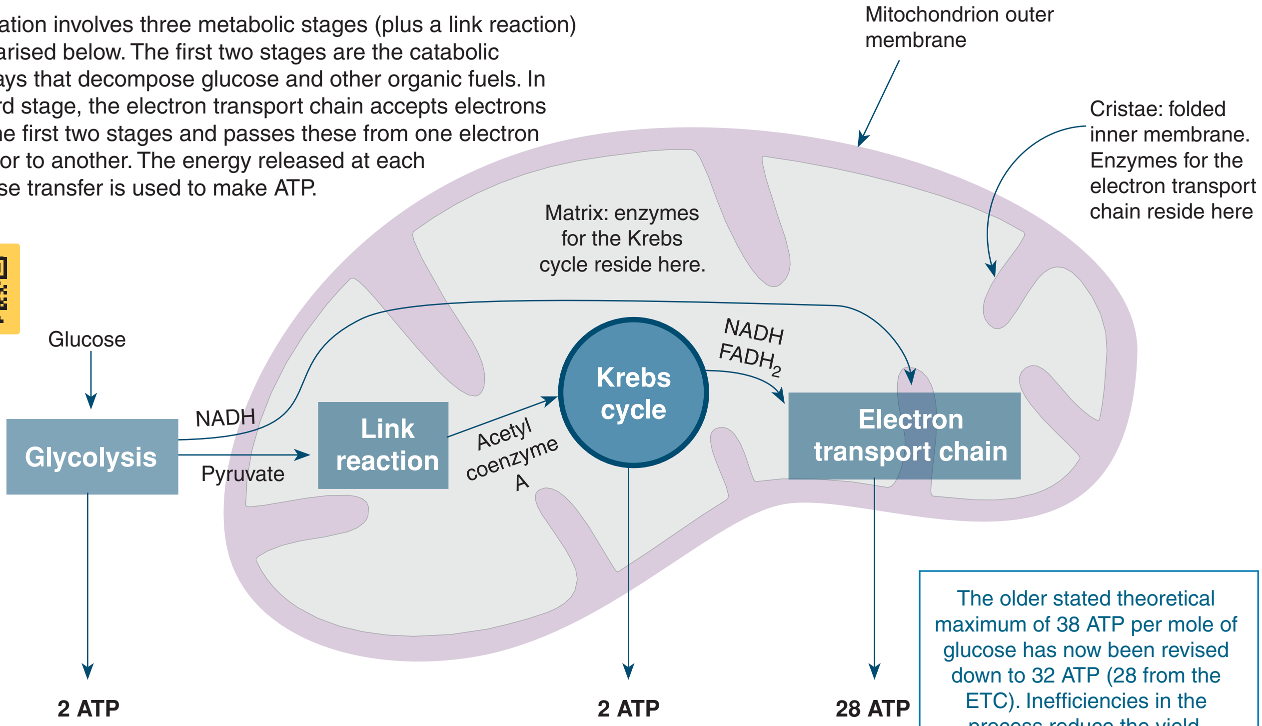
79 Cellular Respiration: Inputs and Outputs

Key Idea: During cellular respiration, the energy in glucose is transferred to ATP in a series of enzyme controlled steps.

The oxidation of glucose is a catabolic, energy yielding pathway. The breakdown of glucose and other organic fuels to simpler molecules is coupled to ATP synthesis. Glycolysis and the Krebs cycle supply electrons to the electron transport chain (ETC), which drives **oxidative phosphorylation**. The conversion of pyruvate (the end product of glycolysis) to **acetyl CoA** links glycolysis to the Krebs cycle. Most of the ATP generated in cellular respiration is produced by oxidative phosphorylation when NADH + H^+ and $FADH_2$ donate electrons to the electron carriers in the ETC. At the end of the chain, electrons are passed to molecular oxygen, reducing it to water. Electron transport is coupled to ATP synthesis.

Overview of cellular respiration

Respiration involves three metabolic stages (plus a link reaction) summarised below. The first two stages are the catabolic pathways that decompose glucose and other organic fuels. In the third stage, the electron transport chain accepts electrons from the first two stages and passes these from one electron acceptor to another. The energy released at each stepwise transfer is used to make ATP.



The older stated theoretical maximum of 38 ATP per mole of glucose has now been revised down to 32 ATP (28 from the ETC). Inefficiencies in the process reduce the yield.

The general equation for cellular respiration

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + ATP$$

1. Describe precisely in which part of the cell the following take place:

   (a) Glycolysis: ______________________________

   (b) Krebs cycle reactions: ______________________________

   (c) Electron transport chain: ______________________________

2. Write a word equation for the general equation for cellular respiration: ______________________________

   ____

3. (a) How many ATP molecules are produced from one glucose molecule during aerobic respiration? ____________

   (b) If one mole of glucose contains 2870 kJ of energy, and one mole of ATP releases 30.7 kJ of energy during a reaction, what is the percentage of energy in glucose that is available for the body to use?

   ____

   ____

4. What is the purpose of NADH and $FADH_2$ in cellular respiration? ______________________________

5. Name three functions of glycolysis in cellular respiration: ______________________________

   ____

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Steps in cellular respiration

Glycolysis
Glycolysis is the beginning of cellular respiration. It takes glucose and produces two pyruvate molecules, each of which can then enter the Krebs cycle. Glycolysis initially uses two ATP but produces four ATP. NADH is produced for use in the electron transport chain. **The numbers shown are for one glucose molecule.**

Link reaction
The link reaction removes CO_2 from pyruvate and adds coenzyme A, producing the 2C molecule acetyl coenzyme A, which enters the Krebs cycle. NADH is also produced and flows to the electron transport chain.

Krebs cycle
In the Krebs cycle, acetyl coenzyme A is attached to the 4C molecule oxaloacetate and coenzyme A is released. Oxaloacetate is eventually remade in a cyclic series of reactions that produce more NADH and $FADH_2$ for the electron transport chain. Two ATP are also made by substrate level phosphorylation.

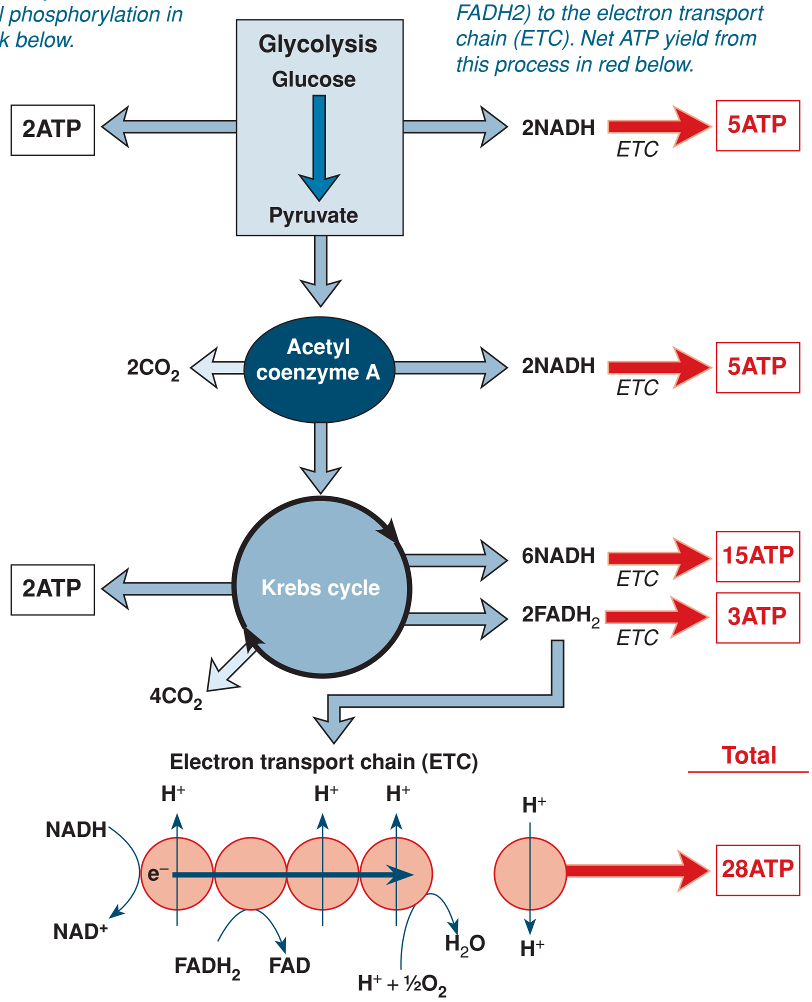
Electron transport chain
Electrons carried by NADH and $FADH_2$ are passed to a series of electron carrier enzymes embedded in the inner membrane of the mitochondria. The energy from the electrons is used to pump H^+ ions across the inner membrane from the matrix into the intermembrane space. These are allowed to flow back to the matrix via the enzyme ATP synthase which uses their energy to produce ATP. The electrons are coupled to H^+ and oxygen at the end of the electron transport chain to form water.

Substrate level phosphorylation

An enzyme transfers a phosphate group directly from a substrate (such as glucose) to ADP to form ATP. Net ATP yield from substrate level phosphorylation in black below.

Oxidative phosphorylation

Glucose is oxidised in a series of reduction and oxidation reactions that provide the energy to form ATP. This is achieved by the flow of reducing power (as NADH and FADH2) to the electron transport chain (ETC). Net ATP yield from this process in red below.



6. Name two functions of the Krebs cycle in cellular respiration: ____________________

____

7. (a) What is substrate level phosphorylation? ____________________

____

(b) How many ATP are produced this way during cellular respiration (per molecule of glucose)? ____________________

8. (a) What is oxidative phosphorylation? ____________________

____

(b) How many ATP are produced this way during cellular respiration (per molecule of glucose)? ____________________

9. Which parts of cellular respiration produce CO_2? ____________________

____

10. Describe how ATP is produced in the electron transport chain: ____________________

____

____

____

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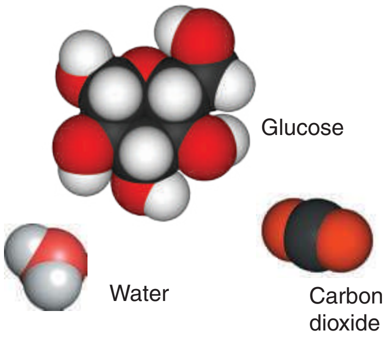
80 Modelling Photosynthesis and Cell Respiration

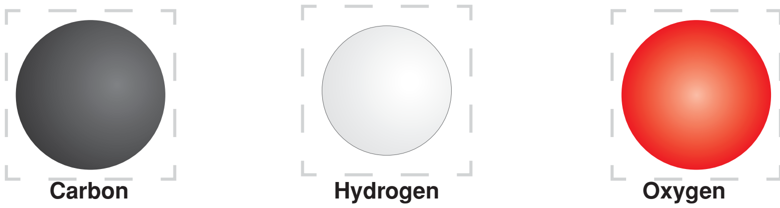
Key Idea: Modelling photosynthesis and cellular respiration using paper cut outs will help you better understand the chemical processes going on.

During photosynthesis and cellular respiration, molecules are broken down and recombined to form new molecules. In this activity you will model the inputs and outputs of each of these processes using the atoms (carbon, hydrogen, and oxygen) on the next page. We have placed the atoms in boxes to make it easier to cut them out. At the end of this activity you will be able to see how the reactants (starting molecules) are recombined to form the final products.

Note: You can either work by yourself or team up with a partner. If you have beads or molecular models you could use these instead of the shapes on the next page.



1. Cut out the atoms and shapes on the following page. They are colour coded as follows:



2. Write the equation for **photosynthesis** here: ______________________________

   (a) State the starting reactants in photosynthesis: ______________________________

   (b) State the total number of atoms of each type needed to make the starting reactants:

   Carbon: ____________ Hydrogen: ____________ Oxygen: ____________

   (c) Use the atoms you have cut out to make the starting reactants in photosynthesis.

   (d) State the end products of photosynthesis: ______________________________

   (e) State the total number atoms of each type needed to make the end products of photosynthesis:

   Carbon: ____________ Hydrogen: ____________ Oxygen: ____________

   (f) Use the atoms you have cut out to make the end products of photosynthesis.

   (g) What do you notice about the number of C, H, and O atoms on each side of the photosynthesis equation? ____________

   ____

   (h) Name the energy source for this process and add it to the model you have made: ____________

3. Write the equation for **cellular respiration** here: ______________________________

   (a) State the starting reactants in cellular respiration: ______________________________

   (b) State the total number of atoms of each type needed to make the starting reactants:

   Carbon: ____________ Hydrogen: ____________ Oxygen: ____________

   (c) Use the atoms you have cut out to make the starting reactants in cellular respiration.

   (d) State the end products of cellular respiration: ______________________________

   (e) State the total number of atoms of each type needed to make the end products of cellular respiration:

   Carbon: ____________ Hydrogen: ____________ Oxygen: ____________

   (f) Use the atoms you have cut out to make the end products of cellular respiration.

   (g) Name the end products of cellular respiration that are utilised in photosynthesis: ____________

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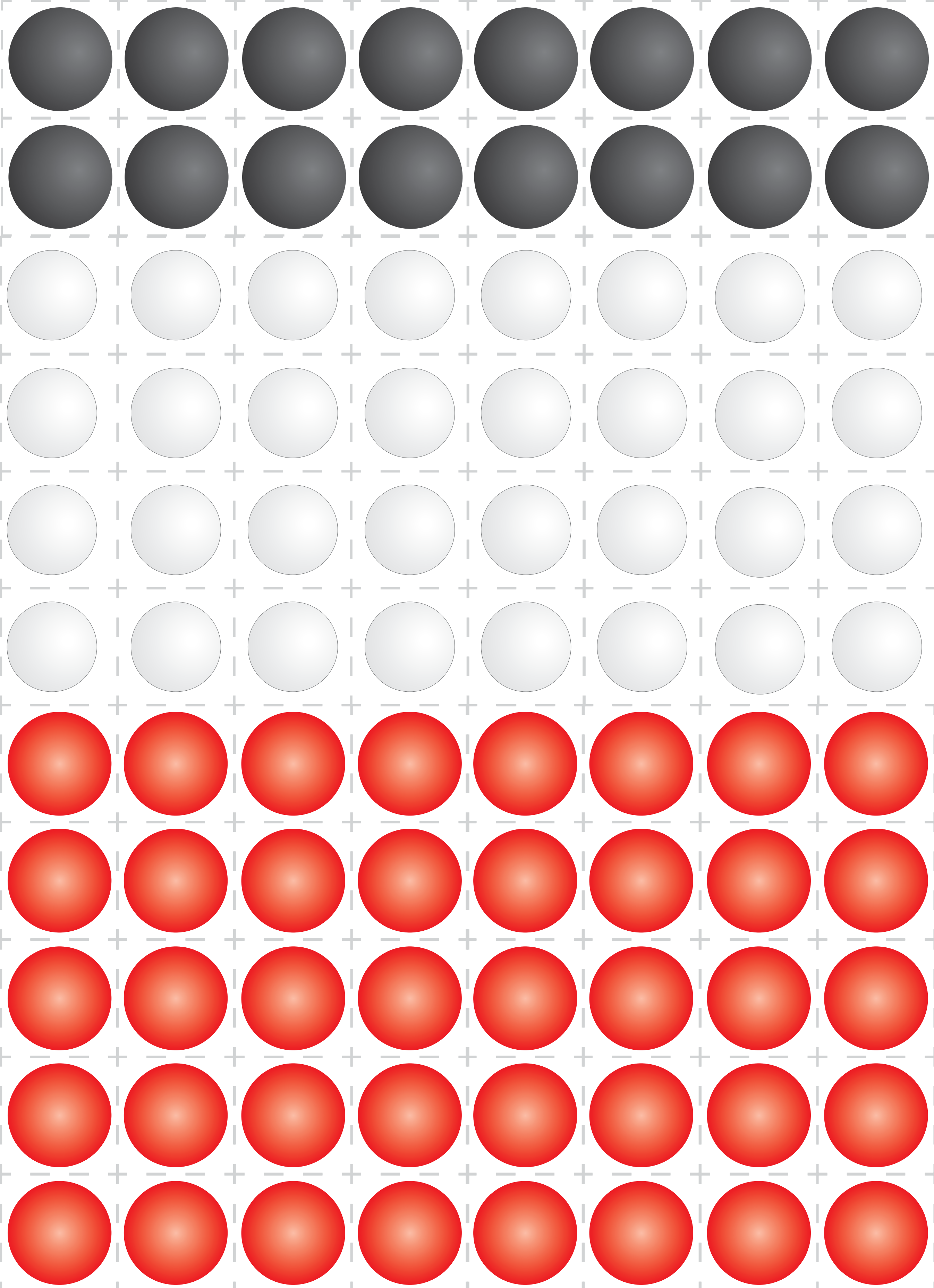

Sunlight energy

→

+

+

ATP

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81 Anaerobic Pathways

Key Idea: Glucose can be metabolised aerobically and anaerobically to produce ATP. The ATP yield from aerobic processes is higher than from anaerobic processes.

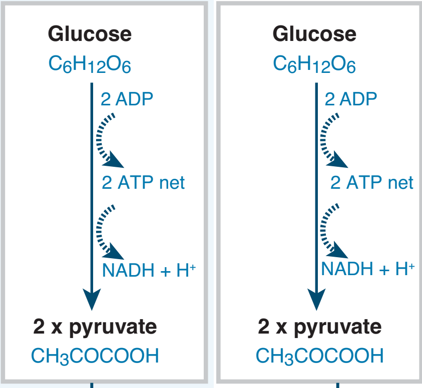
Aerobic respiration occurs in the presence of oxygen. Organisms can also generate ATP when oxygen is absent by using a molecule other than oxygen as the terminal electron acceptor for the pathway. In alcoholic fermentation in yeasts, the electron acceptor is ethanal. In lactic acid fermentation, which occurs in mammalian muscle even when oxygen is present, the electron acceptor is pyruvate itself.

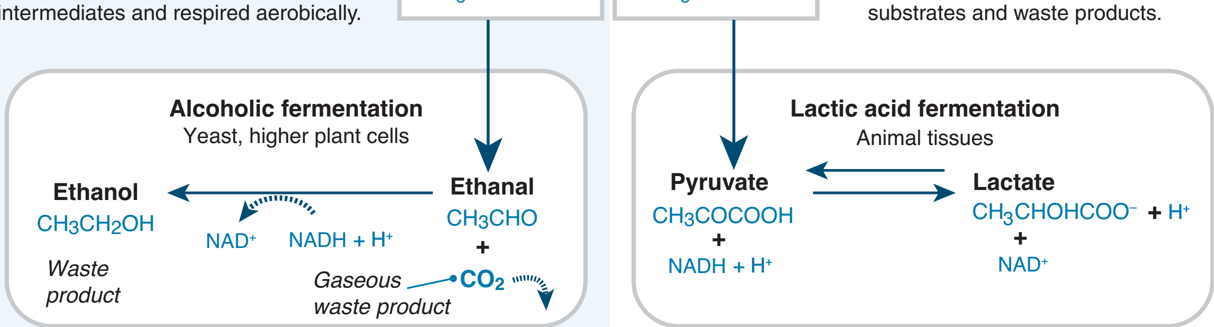
Alcoholic fermentation

In alcoholic fermentation, the H^+ acceptor is ethanal which is reduced to ethanol with the release of carbon dioxide (CO_2). Yeasts respire aerobically when oxygen is available but can use alcoholic fermentation when it is not. At ethanol levels above 12-15%, the ethanol produced by alcoholic fermentation is toxic and this limits their ability to use this pathway indefinitely. The root cells of plants also use fermentation as a pathway when oxygen is unavailable but the ethanol must be converted back to respiratory intermediates and respired aerobically.

Lactic acid fermentation

Skeletal muscles produce ATP in the absence of oxygen using lactic acid fermentation. In this pathway, pyruvate is reduced to lactic acid, which dissociates to form lactate and H^+. The conversion of pyruvate to lactate is reversible and this pathway operates alongside the aerobic system all the time to enable greater intensity and duration of activity. Lactate can be metabolised in the muscle itself or it can enter the circulation and be taken up by the liver to replenish carbohydrate stores. This 'lactate shuttle' is an important mechanism for balancing the distribution of substrates and waste products.





The alcohol and CO_2 produced from alcoholic fermentation form the basis of the brewing and baking industries. In baking, the dough is left to ferment and the yeast metabolises sugars to produce ethanol and CO_2. The CO_2 causes the dough to rise.

Yeasts are used to produce almost all alcoholic beverages (e.g. wine and beers). The yeast used in the process breaks down the sugars into ethanol (alcohol) and CO_2. The alcohol produced is a metabolic by-product of fermentation by the yeast.

Wintec

The lactate shuttle in vertebrate skeletal muscle works alongside the aerobic system to enable maximal muscle activity. Lactate moves from its site of production to regions within and outside the muscle (e.g. liver) where it can be respired aerobically.

1. Describe the key difference between aerobic respiration and fermentation: ______________________

____

____

2. (a) Refer to pages 102-103 and determine the efficiency of fermentation compared to aerobic respiration: __________%

(b) Why is the efficiency of these anaerobic pathways so low? ______________________

____

3. Why can't alcoholic fermentation go on indefinitely? ______________________

____

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82 Investigating Fermentation in Yeast

Key Idea: Brewer's yeast preferentially uses alcoholic fermentation when there is excess sugar, releasing CO_2, which can be collected as a measure of fermentation rate.

Brewer's yeast is a facultative anaerobe (meaning it can respire aerobically or use fermentation). It will preferentially use alcoholic fermentation when sugars are in excess. One would expect glucose to be the preferred substrate, as it is the starting molecule in cellular respiration, but brewer's yeast is capable of utilising a variety of sugars, including disaccharides, which can be broken down into single units.

The aim

To investigate the suitability of different mono- and disaccharide sugars as substrates for alcoholic fermentation in yeast.

The hypothesis

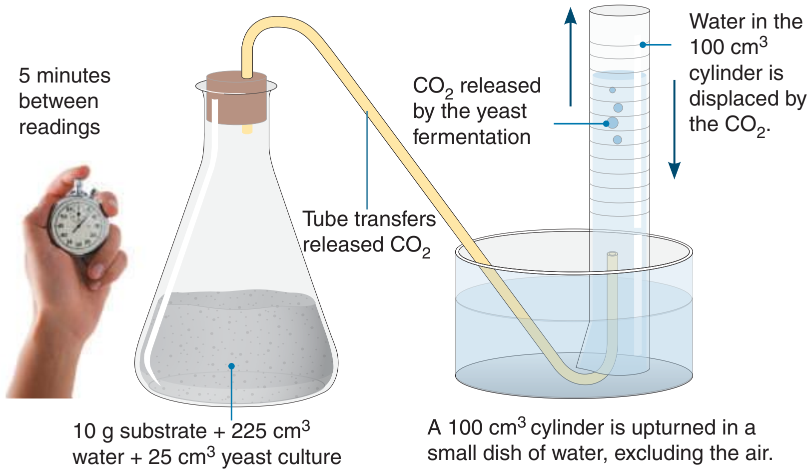
If glucose is the preferred substrate for fermentation in yeast, then the rate of fermentation will be highest when the yeast is grown on glucose rather than on other sugars.

Background

The rate at which brewer's or baker's yeast (*Saccharomyces cerevisiae*) metabolises carbohydrate substrates is influenced by factors such as temperature, solution pH, and type of carbohydrate available.

The literature describes yeast metabolism as optimal in warm, acid (pH 4-6) environments.

High levels of sugars suppress aerobic respiration in yeast, so yeast will preferentially use the fermentation pathway in the presence of excess substrate.



The apparatus

In this experiment, all substrates tested used the same source culture of 30 g active yeast dissolved in 150 cm^3 of room temperature (24°C) tap water. 25 g of each substrate to be tested was added to 225 cm^3 room temperature (24°C) tap water buffered to pH 4.5. Then 25 cm^3 of source culture was added to the test solution. The control contained yeast solution but no substrate.

The substrates

Glucose is a monosaccharide, maltose (glucose-glucose), sucrose (glucose-fructose), and lactose (glucose-galactose) are disaccharides.

Substrate / Time (min)	Volume of carbon dioxide collected (cm^3)				
	None	Glucose	Maltose	Sucrose	Lactose
0	0	0	0	0	0
5	0	0	0.8	0	0
10	0	0	0.8	0	0
15	0	0	0.8	0.1	0
20	0	0.5	2.0	0.8	0
25	0	1.2	3.0	1.8	0
30	0	2.8	3.6	3.0	0
35	0	4.2	5.4	4.8	0
40	0	4.6	5.6	4.8	0
45	0	7.4	8.0	7.2	0
50	0	10.8	8.9	7.6	0
55	0	13.6	9.6	7.7	0
60	0	16.1	10.4	9.6	0
65	0	22.0	12.1	10.2	0
70	0	23.8	14.4	12.0	0
75	0	26.7	15.2	12.6	0
80	0	32.5	17.3	14.3	0
85	0	37.0	18.7	14.9	0
90	0	39.9	21.6	17.2	0

Experimental design and results adapted from Tom Schuster, Rosalie Van Zyl, & Harold Coller, California State University Northridge 2005

1. Write the equation for the fermentation of glucose by yeast:

   ____

2. The results are presented on the table left. Using the final values, calculate the rate of CO_2 production per minute for each substrate:

   (a) None: ____________

   (b) Glucose: ____________

   (c) Maltose: ____________

   (d) Sucrose: ____________

   (e) Lactose: ____________

3. What assumptions are being made in this experimental design and do you think they were reasonable?

   ____

   ____

   ____

   ____

   ____

   ____

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4. Use the tabulated data to plot an appropriate graph of the results on the grid provided:

5. Identify the independent variable:

6. (a) Identify the dependent variable:

(b) Name the unit for the dependent variable:

7. (a) Summarise the results of the fermentation experiment:

(b) Why do you think CO_2 production was highest when glucose was the substrate?

(c) Suggest why fermentation rates were lower on maltose and sucrose than on glucose:

(d) Suggest why there may have been no fermentation on the lactose substrate:

8. Predict what would happen to CO_2 production rates if the yeast cells were respiring aerobically:

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83 KEY TERMS AND IDEAS: Did You Get It?

1. Test your vocabulary by matching each term to its correct definition, as identified by its preceding letter code

ATP	**A**	The organelle found in the cells of green plants where photosynthesis takes place. It contains the green pigment chlorophyll and other pigments involved with photosynthesis.
aerobic respiration	**B**	Chain of enzyme-based redox reactions, which passes electrons from high to low redox potentials. The energy released is used to produce ATP.
cellular respiration	**C**	Respiration requiring oxygen as the terminal electron acceptor.
chlorophyll	**D**	A nucleotide derivative, which acts as the cell's energy carrier.
chloroplast	**E**	Part of a metabolic pathway involved in the chemical conversion of carbohydrates, fats and proteins to CO_2 and water to generate a form of usable energy (ATP).
electron transport chain	**F**	An anaerobic process in which pyruvate is converted to lactic acid or to ethanol and carbon dioxide.
fermentation	**G**	The biochemical process that uses light energy to convert carbon dioxide and water into glucose molecules and oxygen.
glycolysis	**H**	The catabolic process in which the chemical energy in complex organic molecules is coupled to ATP production.
Krebs cycle	**I**	A series of reactions that converts glucose into pyruvate. The energy released is used to produce ATP.
mitochondria	**J**	A photosynthetic pigment that strongly absorbs red and blue-violet light and appears green in colour.
photosynthesis	**K**	Organelles responsible for producing the cell's ATP. They appear oval in shape with an outer double membrane and a convoluted interior membrane.

2. (a) What process is represented by the following equation: $H_2O + CO_2 \rightarrow C_6H_{12}O_6 + O_2$

(b) Where does this process occur? ______

3. (a) Label the following features of a chloroplast on the diagram below: granum, stroma, thylakoid disc, stroma lamellae.

(b) Indicate on the diagram where the light dependent and light independent reactions occur.

4. Outline the differences between photosynthesis and cellular respiration, including reference to the raw materials used and the waste products produced:

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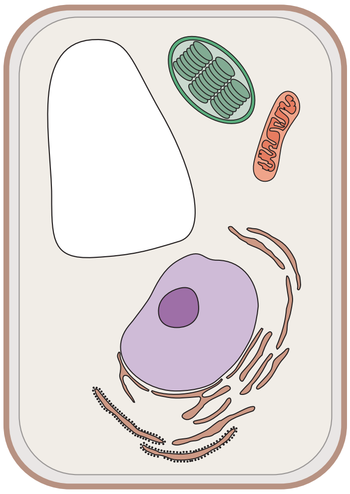
84 Synoptic Question: Unit 1 Topic 1

1. (a) Plant cells are eukaryotic cells. Annotate the following diagram to identify the features of a plant cell. In your answer you should briefly state the function of the structures and organelles labelled.



(b) Which organelle shown in the plant cell is not found in an animal cell? ______________________

2. Describe the characteristics of the plasma membrane and discuss how substances are transported across it. Include simple diffusion, facilitated diffusion, osmosis, and active transport. You may use extra paper if required.

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3. Enzymes are essential for catalysing biological reactions. Describe the induced fit model of enzyme action: ____________

4. Identify the following statements as true of false (circle one)

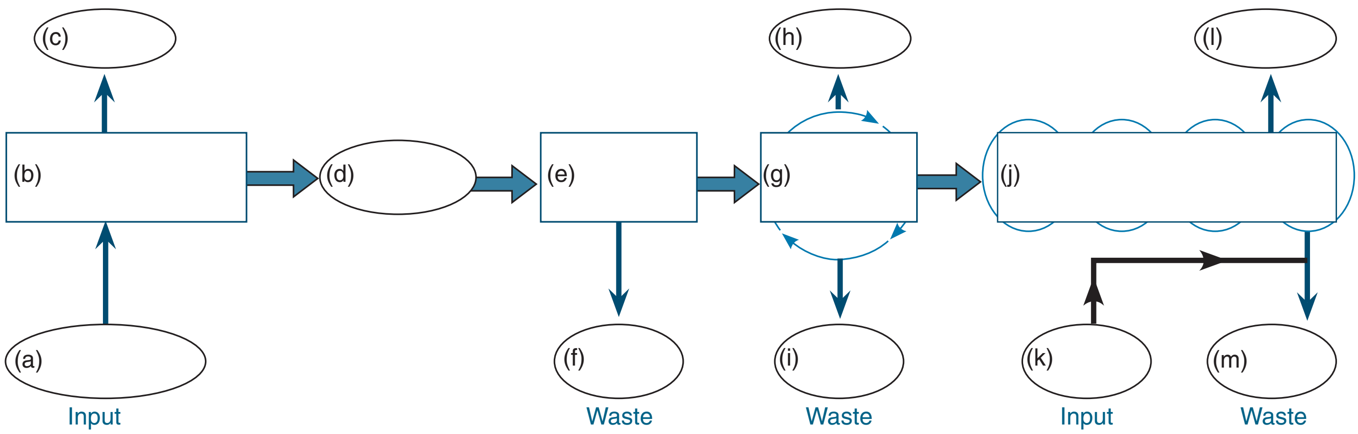
(a) Enzymes are biological catalysts. They lower the activation energy of a reaction. True / False

(b) Competitive inhibition is when an inhibitor binds to a site other than the active site. True / False

(c) The induced fit model states that the enzyme changes shape when a substrate fits into the active site. True / False

(d) End product inhibition causes a feedback loop that escalates the outcome of the loop. True / False

5. Cellular respiration is a continuous, integrated process. A simple diagram of the process in a eukaryote is shown below.
(a) In the diagram, fill in the rectangles with the process and the ovals with the substance used or produced. Use the following word list (some words can be used more than once): *pyruvate, glycolysis, glucose, oxygen (O_2), link reaction, electron transport chain (ETC), Krebs cycle, ATP, carbon dioxide (CO_2)*, water (*H_2O*)
(b) Add in a pathway to show fermentation. Write the two possible products of this pathway in eukaryotes.

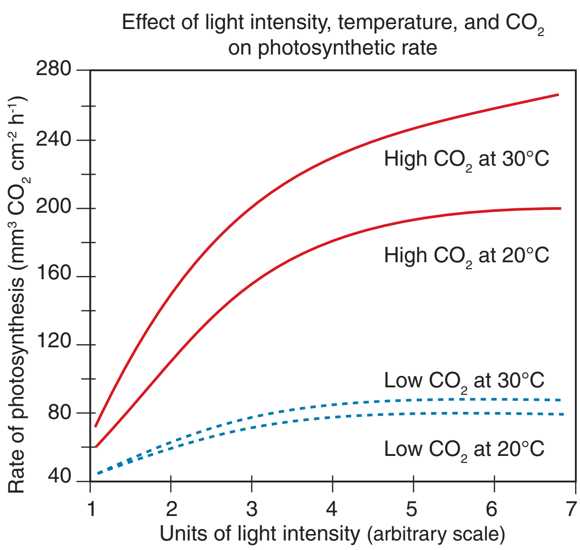


(c) Use the completed diagram to explain the difference in ATP yield between aerobic and anaerobic pathways:

6. Based on the graph right, summarise and explain the effect of each of the following factors on photosynthetic rate:

(a) CO_2 concentration: ____________

(b) Temperature: ____________



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UNIT 1
Topic 2

Cellular Differentiation and Specialisation

Key terms

adult stem cell
bioartificial tissue
cell specialisation
cellular differentiation
embryonic stem cell
multipotent
organ
pluripotent
potency
self renewal
specialised cell
stem cell
tissue
totipotent
zygote

Activity number

Types and properties of stem cells

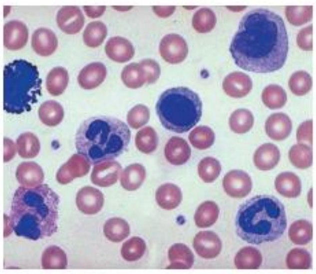
Key skills and knowledge

☐ 1 Explain what is meant by a stem cell and explain how they differ from other cells. Describe the properties of stem cells, including self-renewal and potency. **85**

☐ 2 Describe the role of stem cells in producing (through cellular differentiation) the specialised cells that make up the tissues and organs of multicellular organisms. Distinguish between embryonic stem cells (ESC) and adult stem cells (ASC) and their role in the developing and the adult organism. **85 87**

☐ 3 Distinguish between the potency of different stem cell types, including totipotent, pluripotent, and multipotent stem cells. Understand that as cells become more specialised during division of the zygote they lose their ability to produce different cell types and eventually become committed to their specialised state. **85**

☐ 4 **SHE** Discuss the use of ASC and ESC in medical technology. Analyse data and evaluate alternative perspectives on the use of stem cell research. **85 86**



Multicellular organisms have a hierarchical structure

Key skills and knowledge

☐ 5 Using examples, describe the hierarchical structure of multicellular organisms, including reference to cells, tissues, organs, and organ systems. **88**

☐ 6 Explain how a hierarchical organisation builds structural complexity and contributes to the functional efficiency of the organism as a whole. Include reference to emergent properties (the whole is greater than the sum of the parts). **88-90**

☐ 7 **PRAC** Explore aspects of hierarchical organisation through a dissection of a mammalian organ such as a heart or kidney. How does the arrangement of tissues produce the organ's structure and contribute to function? **89**

☐ 8 Recognise that organ systems can cooperate and interact to deliver essential functions such as transport of respiratory gases and nutrients. **90**

Stem Cells and Bioartificial Organs

Key skills and knowledge

☐ 9 Explain how cells from a patient or stem cell bank can be used to produce bioartificial tissues and organs as an alternative to donor tissues and organs. What are the benefits of growing organs in the lab and what technical difficulties are associated with this technology? **91**

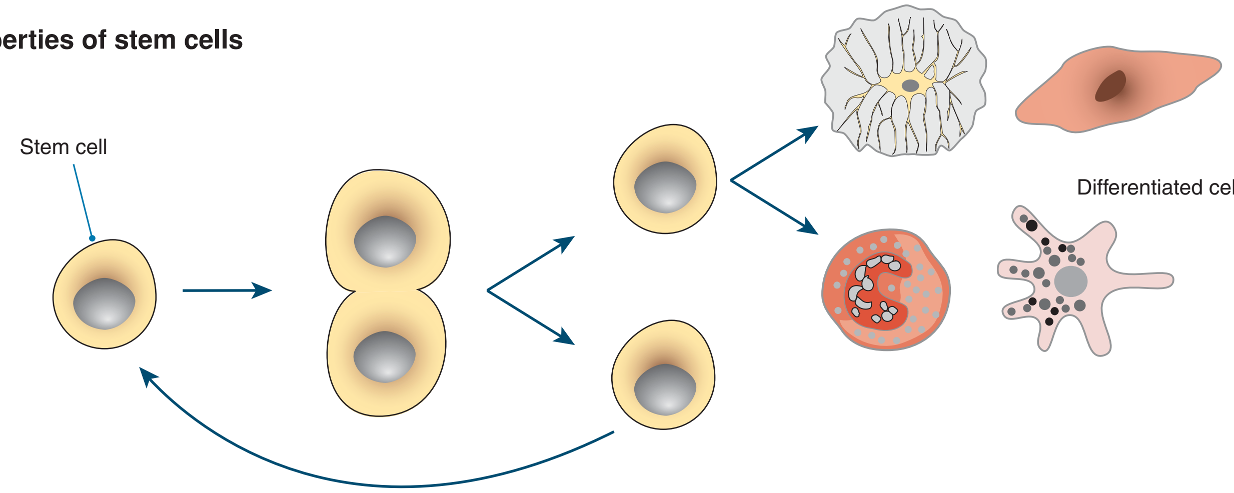
☐ 10 **SHE** Recognise the importance of ethical treatment when using animals in research of any kind. Describe the three strategies of replacement, reduction, and refinement that underpin ethical guidelines internationally and explain what they mean. **91**

85 What are Stem Cells?

Key Idea: Stem cells are undifferentiated cells found in multicellular organisms. They are characterised by the properties of self renewal and potency.

A zygote can differentiate into all the cell types of the body because its early divisions produce stem cells. Stem cells are unspecialised cells that can divide repeatedly while remaining unspecialised. They give rise to the many cell types that make up the tissues of a multicellular organism. For example, the stem cells in bone marrow specialise to produce all the cell types that make up blood. These multipotent (or adult) stem cells are found in most organs, where they replace old or damaged cells and replenish cells throughout life.

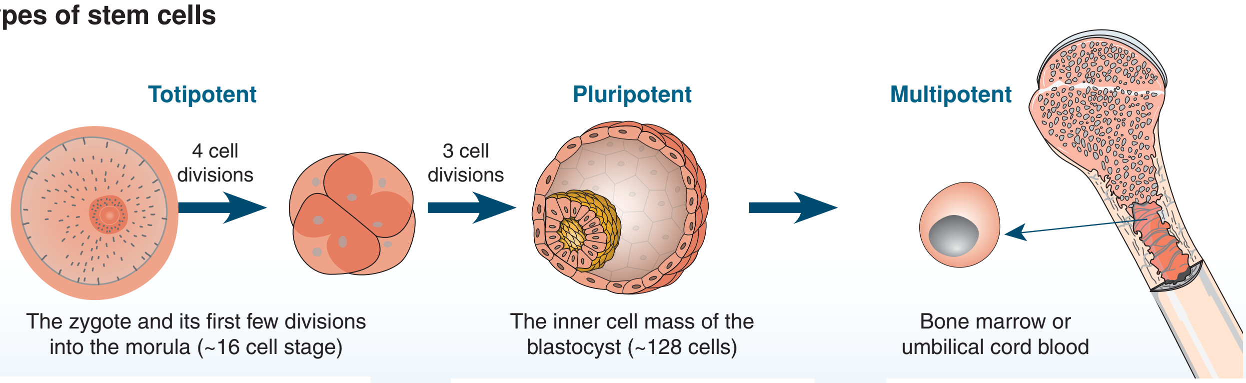
Properties of stem cells



Self renewal: Stem cells have the ability to divide many times while maintaining an unspecialised state.

Potency: The ability to differentiate (transform) into specialised cells. There are different levels of potency, depending on the type of stem cell.

Types of stem cells



The zygote and its first few divisions into the morula (~16 cell stage)

The inner cell mass of the blastocyst (~128 cells)

Bone marrow or umbilical cord blood

Totipotent stem cells
These stem cells can differentiate into all the cells in an organism. Example: In humans, the zygote and its first few divisions. The tissue at the root and shoot tips of plants is also totipotent.

Pluripotent stem cells
These stem cells can give rise to any cells of the body, except extra-embryonic cells (e.g. placenta and chorion). Example: Embryonic stem cells.

Multipotent stem cells
These adult stem cells can give rise to a limited number of cell types, related to their tissue of origin. Example: Bone marrow stem cells, epithelial stem cells, bone stem cells (osteoblasts).

1. Describe the two defining features of stem cells:

(a) ____________________

(b) ____________________

2. Describe the potency of stem cells and where they are found:

(a) Totipotency: ____________________

____

(b) Pluripotency: ____________________

____

(c) Multipotency: ____________________

____

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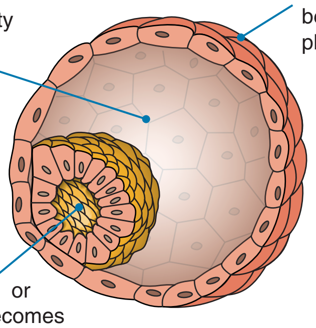
Embryonic stem cells



- **Embryonic stem cells** (**ESC**) are derived from the inner cell mass of blastocysts (above). Blastocysts are 5 day old embryos consisting of a hollow ball of 50-150 cells.
- Cells derived from the inner cell mass are **pluripotent**. They can become any cells of the body, with the exception of placental cells.
- When cultured without any stimulation to differentiate, ESC retain their potency through multiple cell divisions. This means they have great potential for therapeutic use in regenerative medicine and tissue replacement.
- However, the use of ESC involves the deliberate creation and destruction of embryos and is therefore is ethically unacceptable to many people.

Adult stem cells

- **Adult stem cells** (ASC) are undifferentiated cells found in several types of tissues (e.g. brain, bone marrow, fat, and liver) in adults, children, and umbilical cord blood.
- Unlike ESCs, they are **multipotent** and can only differentiate into a limited number of cell types, usually related to the tissue of origin.
- There are fewer ethical issues associated with using ASC for therapeutic purposes, because no embryos are destroyed. For this reason, ASC are already widely used to treat a number of diseases including leukaemia and other blood disorders.

3. Distinguish between embryonic stem cells and adult stem cells with respect to their potency: ______________________

4. Suggest how stem cells could be potentially useful for treating diseased or damaged organs: ______________________

5. Why are there ethical issues with the use of embryonic stem cells in research and medicine? ______________________

6. New research has produced pluripotent stem cells from differentiated adult cells. These are called induced pluripotent stem cells. Suggest why using these cells in medicine generates fewer ethical issues than using other stem cell types?

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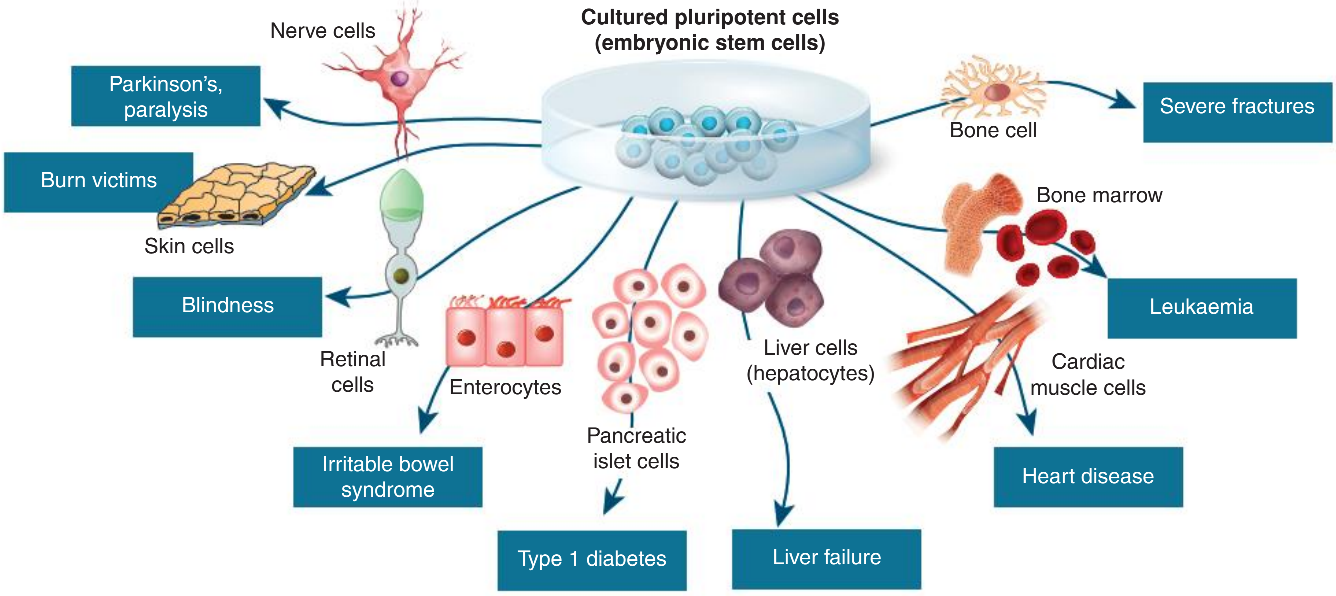
86 Applications of Stem Cells

Key Idea: Stem cells have many potential medical applications, but technical difficulties must be overcome first.

Stem cell research is at an early stage and there is much to be learned about the environments that cells require in order to differentiate into specific cell types. The ability of embryonic stem cells (ESC) to differentiate into almost any cell type means that they have potential applications in replacing diseased or damaged cells (below). Adult stem cells, either from a donor or from the patient themselves, also have therapeutic uses. Donor stem cells must be matched for compatibility, while stem cell cells for autologous transplants may require genetic correction before use (lower panels).

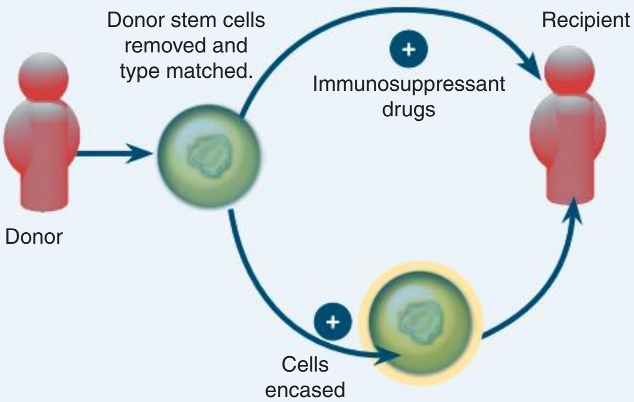


Donor stem cells can be used to repair tissues

Problem: Immune system will attack the donor's cells.

Solution: Firstly, a donor with a tissue match is selected (the cell surface proteins on donor and recipient cells are the same or very similar). This reduces the risk of immune rejection. Secondly, the recipient will need to take immunosuppressant drugs to stop their immune system attacking the donated cells.

Another way to prevent immune rejection is to encase donor cells in a protective shell, isolating them from immune detection by the recipient. This is being investigated with respect to pancreatic cells and diabetes.

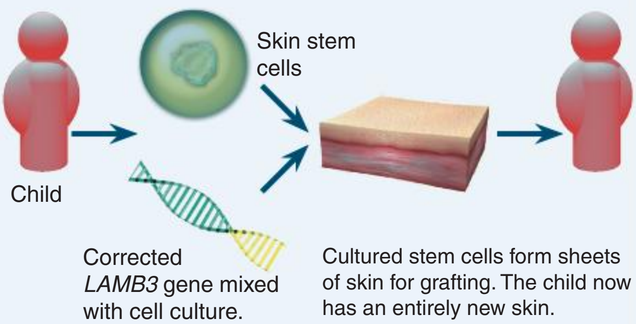


A patient's cells can be corrected before use

Problem: Some diseases are the result of defective genes. Stem cells from the patient will carry these defective genes.

Solution: If the disease is due to a simple genetic fault, then the stem cells can be genetically corrected before use. Stem cells are isolated and cultured in the laboratory in the presence of the corrected gene. Corrected cells are identified and transplanted back into the patient, without immune rejection.

Example: In 2015, a young German child had a mutation in the *LAMB3* gene. His skin cells were not making the protein needed to hold cells together and his skin was falling off. His skin stem cells were genetically corrected and new skin was cultured and grafted back. More than a square metre of skin was grown and grafted on to the child.



1. Identify a problem with using stem cells from a donor to treat a recipient patient: ______________________

____

____

____

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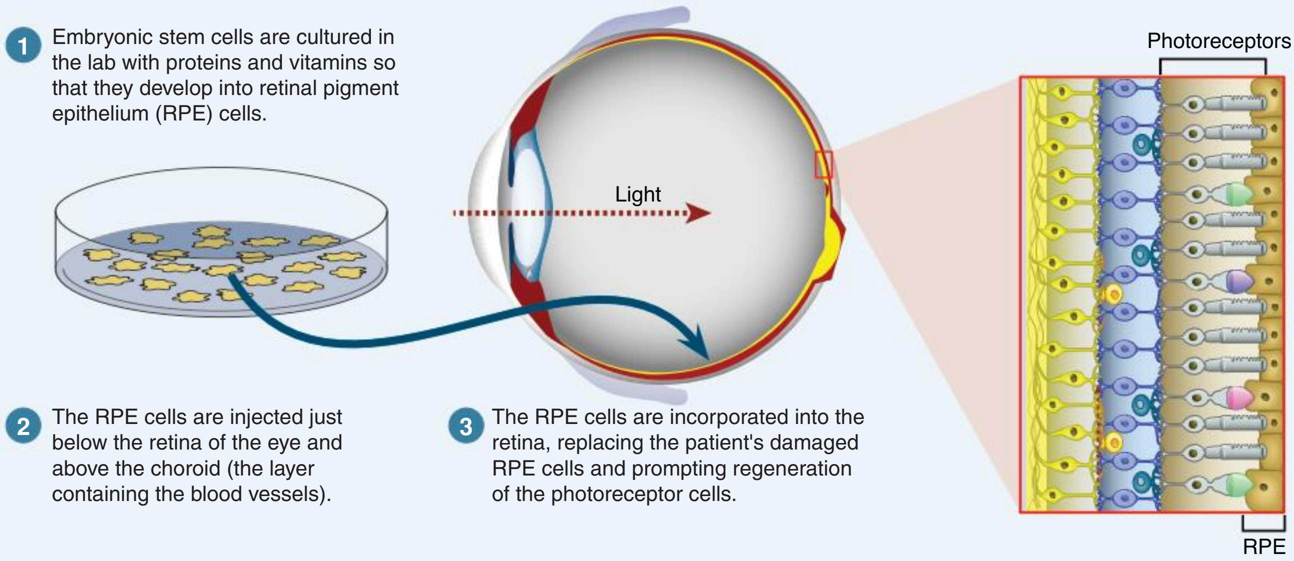
SHE

Stem cells for Stargardt's disease

- Stargardt's disease is an inherited form of juvenile macular degeneration (a loss of the central visual field of the eye). The disease is associated with a number of different mutations and results in malfunction of the retinal pigment epithelium (RPE) cells, which normally nourish the retinal photoreceptor cells and protect the retina from excess light.
- Faulty RPE causes deterioration of the photoreceptor cells in the centre of the retina and progressive loss of central vision. This often begins between ages 6 and 12 and continues until a person is legally blind. Trials using stem cells have proved promising as a treatment, with impaired vision being corrected relatively quickly (within weeks).



2. Umbilical cord blood is promoted as a rich source of multipotent stem cells for autologous (self) transplants. Can you see a problem with using a baby's cord blood to treat a disease in that child at a later date?

3. (a) Explain the basis for correcting Stargardt's disease using stem cell technology:

   (b) There have also been stem cell therapy trials using the patient's own cells (e.g. bone marrow) to treat Stargardt's disease. What advantages might there be in using a patient's own cells and what difficulties might be involved?

4. Describe a technical difficulty associated with stem cell therapies when:

   (a) The stem cells come from a donor:

   (b) The stem cells used are ESC:

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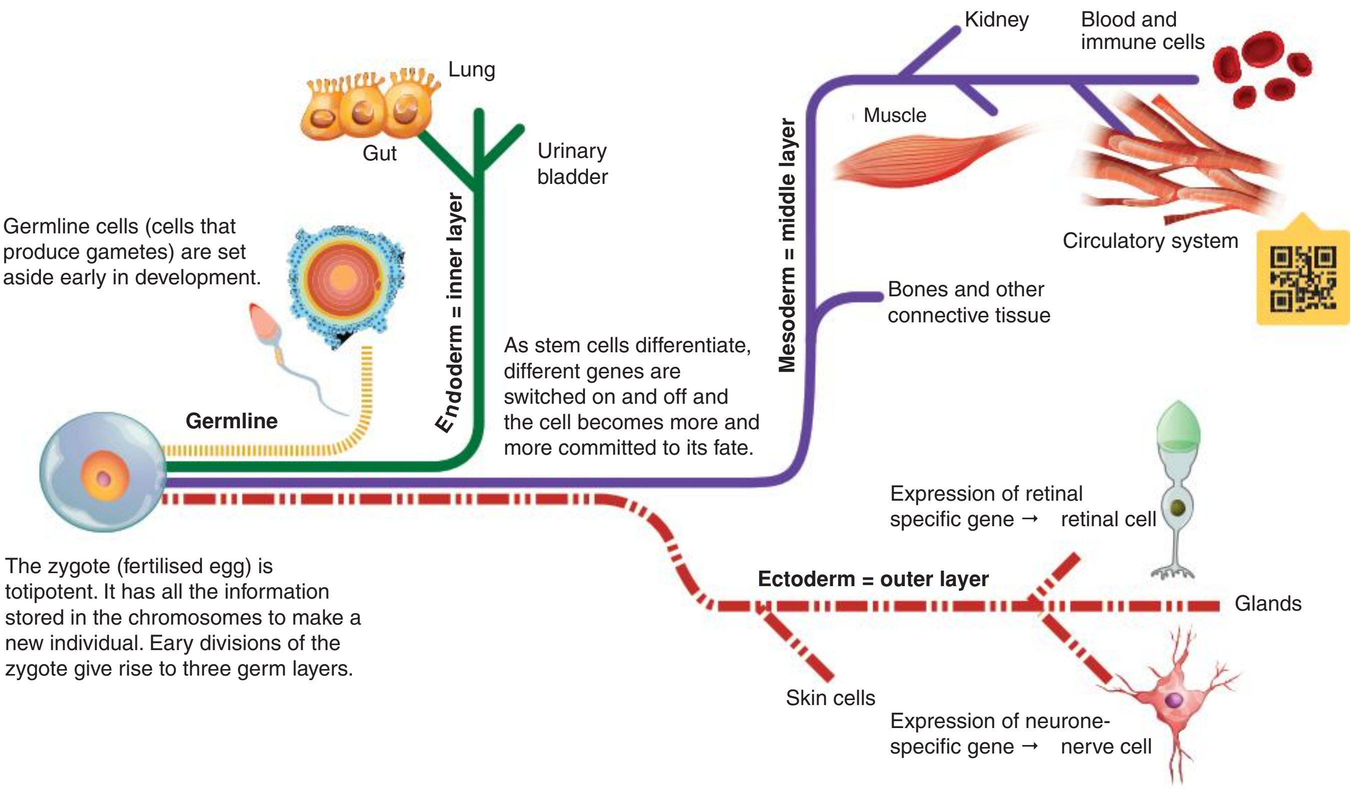
87 Cellular Differentiation

Key Idea: A zygote divides and produces all the cell types in the body by cellular differentiation. Specific patterns of gene switching determine what cell type develops.

As described, multicellular organisms consist of many different cell types, each specialised to carry out a particular role. A zygote and its first few divisions are totipotent and can differentiate to form any cell type in the body. During development, these cells divide and follow different developmental pathways, giving rise to the three germ layers and the specialised cells that make up the tissues and organs of the body. This process by which more specialised cells develop from more generalised ones is called **cellular differentiation** and it is achieved through switching genes on and off in particular sequences. As a cell proceeds along its developmental pathway, its 'choices' become more limited. Once fully differentiated, it can not turn into another cell type.



1. Multicellular organisms consist of many different cell types. Explain how it is possible for these all to arise from a single fertilised egg (zygote):

____

____

____

____

2. The zygote produces cells the differentiate in three cell lineages (germ layers). What types of cells/tissues do each of these lineages produce?

   (a) Endoderm: _______________

   ____

   (b) Mesoderm: _______________

   ____

   (c) Ectoderm: _______________

   ____

3. Why can't a blood cell turn into a nerve cell? _______________

____

____

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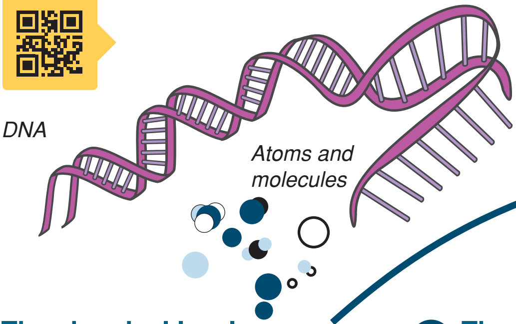
88 The Hierarchy of Life

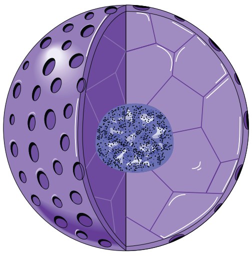
Key Idea: Structural organisation in multicellular organisms is hierarchical, with new properties arising at each level.

Multicellular organisms are organised according to a hierarchy of structural levels, where each level builds on the one below it. At each level, new properties, absent at the simpler level, emerge. Hierarchical organisation allows specialised cells to group together into tissues and organs to perform a specific function or set of related functions. This improves efficiency in the organism. Organisation and the emergence of new properties in complex systems are two of the defining features of living organisms. The diagrams following explain this hierarchical organisation for a human and a plant.



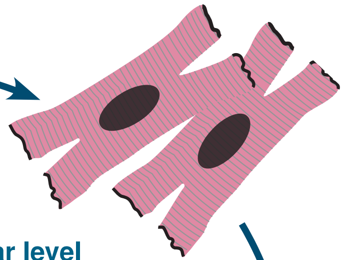
1 The chemical level

All the chemicals essential for maintaining life, e.g. water, ions, fats, carbohydrates, amino acids, proteins, and nucleic acids.



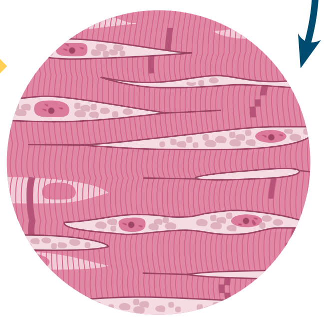
2 The organelle level

Molecules associate together to form the organelles and structural components of cells, e.g. the nucleus (above).



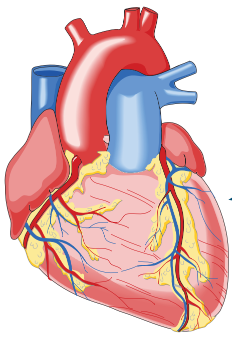
3 The cellular level

Cells are the basic structural and functional units of organisms. Cells are specialised to carry out specific functions, e.g. contraction of cardiac muscle cells.



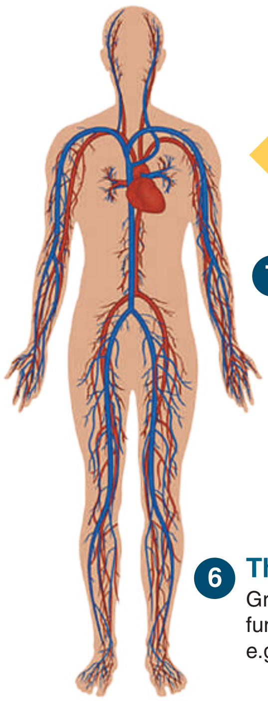
4 The tissue level

Groups of cells with related functions form tissues, e.g. cardiac (heart) muscle (above). The cells of a tissue often have a similar origin.



5 The organ level

An organ is made up of two or more types of tissues to carry out a particular function. Organs have a definite form and structure, e.g. heart (left).



6 The organ system level

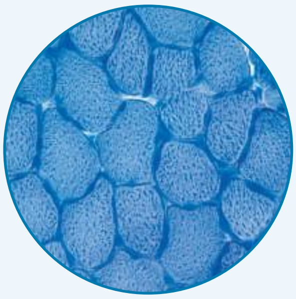
Groups of organs with a common function form an organ system, e.g. cardiovascular system (left).

7 The organism

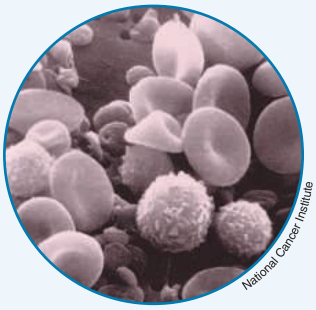
The cooperating organ systems make up the organism, e.g. a human.

Specialised cells make up tissues and organs

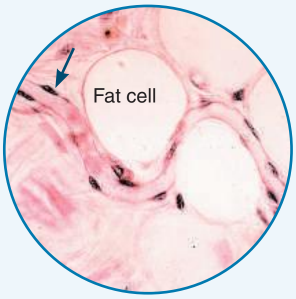
Specialised cells often have modifications or exaggerations to a normal cell feature to help them perform a particular task. They may have more (or fewer) of a particular organelle in order to perform their role most efficiently.



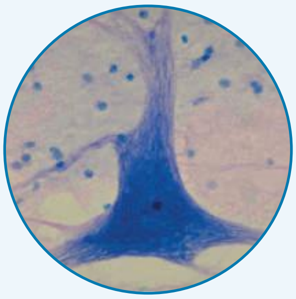
Muscle cells are able to contract (shorten) to bring about the movement of limbs and organs.



There are many types of blood cell, each with a specific task.



Thin, flat epithelial cells line the walls of blood vessels (arrow). Large fat cells store lipid.



Nerve cells conduct impulses around the body enabling responses to the environment.

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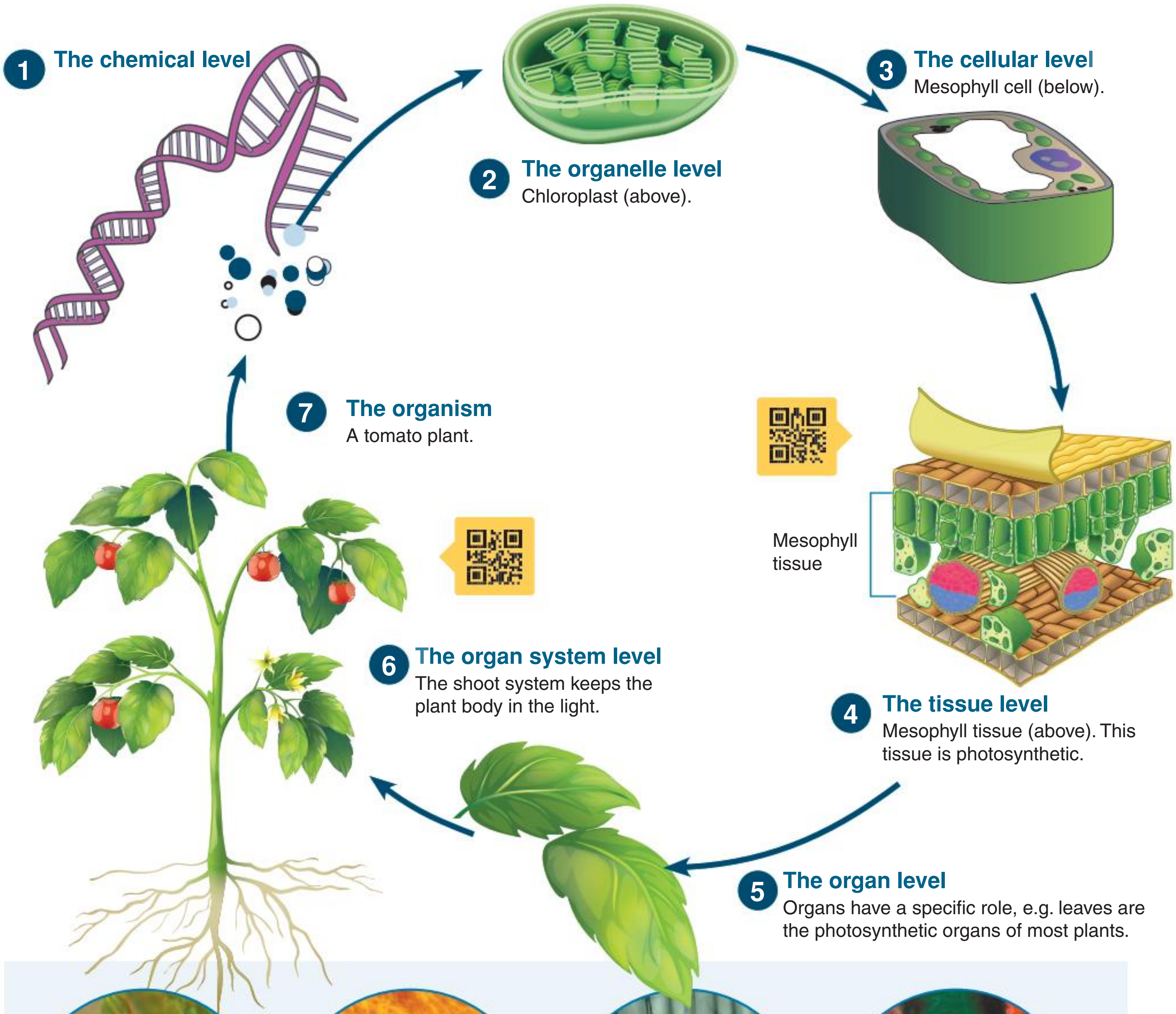
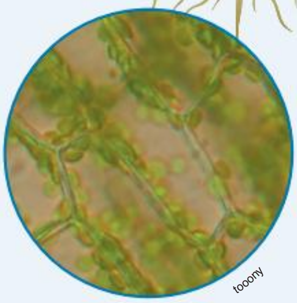
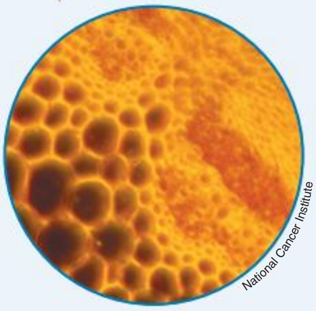
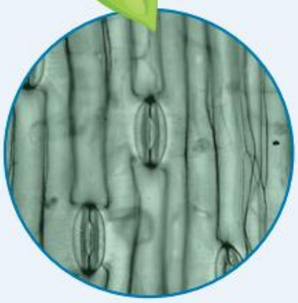




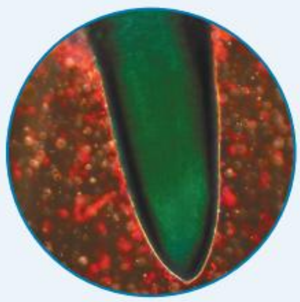
Cells of the leaf mesophyll tissue are packed with chloroplasts. Leaf structure maximises light capture.



The thick-walled vessels of xylem tissue transport water and are important in supporting the plant body.



The stomata (pores) in the leaf epidermis allow gases to enter and leave the leaf. Guard cells help regulate these exchanges.



At the root tip, thin-walled extensions of the epidermis maximise surface area for exchanges of nutrients and water.

1. Assign each of the following emergent properties to the level at which it first appears:

(a) Metabolism: ______________________

(b) Behaviour: ______________________

(c) Replication: ______________________

(d) Internal transport: ______________________

(e) Surface protection: ______________________

(f) Nutrient processing: ______________________

2. Explain how a hierarchical structure enables greater efficiency of function in the whole organism: ______________________

____

____

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89 Exploring Tissues and Organs

Key Idea: Tissues come together to make organs. You can see this in an isolated organ, such as a heart.

A tissue is a collection of related cell types that work together to carry out a specific function. Different tissues come together to form organs. The cells, tissues, and organs of the body interact to meet the needs of the entire organism. You can explore the different tissues that make up an organ by examining an isolated organ, such as a sheep's heart.

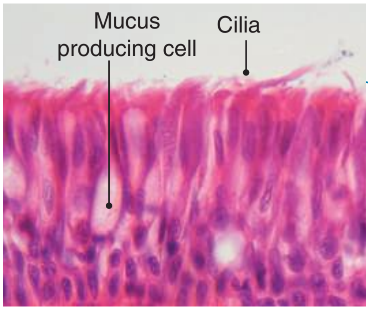
Muscle tissue
- Contractile tissue
- Produces movement of the body or its parts
- Includes smooth, skeletal, and cardiac muscle

Epithelial tissue
- Lining tissue
- Covers the body and lines internal surfaces
- Can be modified to perform specific roles

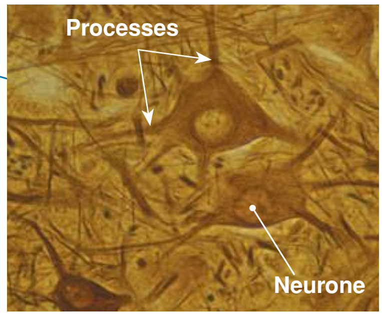
Nervous tissue
- Receives and responds to stimuli
- Makes up the structures of the nervous system
- Regulates function of other tissues

Connective tissue
- Supports, protects, and binds other tissues
- Contains cells in an extracellular matrix
- Can be hard or fluid

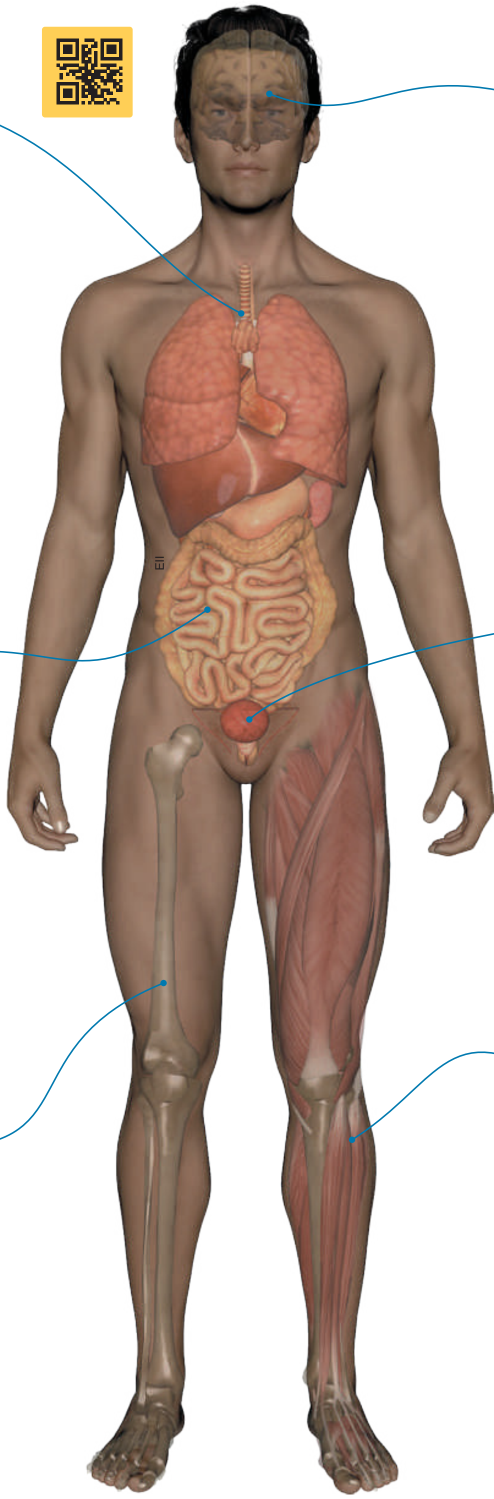
1. Research the type of tissue(s) that occur at the places in the body indicated below. State the types of tissues that occur in the spaces provided. Codes: E = epithelium, CT = connective tissue, SM = smooth muscle.

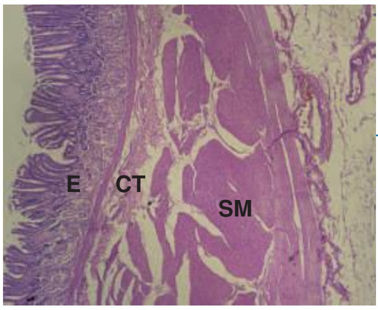


Upper respiratory tract:

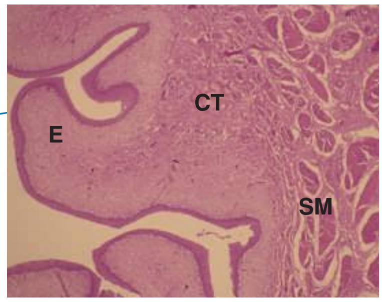


Brain:

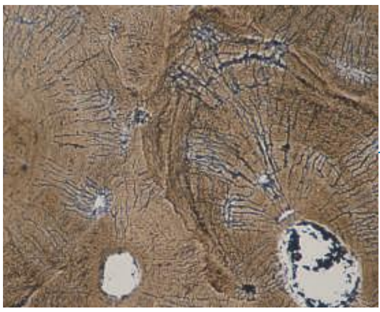




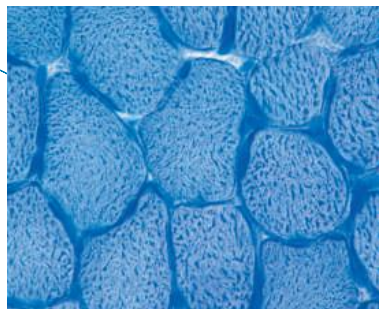
Digestive tract:



Bladder:



Bone:



Skeletal muscle:

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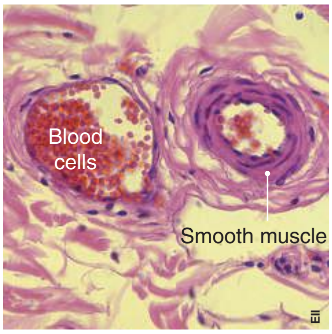
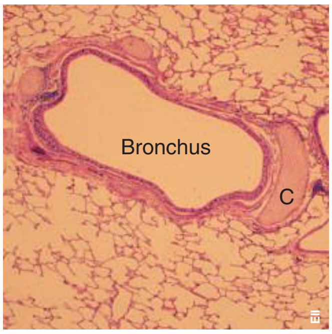
Tissues work together and make up organs, which perform specific functions

The body's tissues work together in order for the body to function. Tissues also group together to form organs. For example, epithelial tissues are found associated with other tissues in every organ of the body. Similarly blood vessels and nerves, which may be very small, supply all tissues. For the gas exchange and the circulatory systems:



Blood (a liquid connective tissue) flows within blood vessels, such as the vein (left) and artery (right) above. Note the thick layer of smooth muscle in the artery wall.



Lung tissue is made up of thin-walled sacs lined with epithelium. Airways (bronchi) are supported with cartilage (C) and have a small amount of muscle.

Most of the heart is a type of muscle tissue called cardiac muscle. Fat and other connective tissues anchor and support the heart and blood vessels.

The trachea, which carries air to the lung is reinforced with tough rings of cartilage (a connective tissue), lined with epithelium (shiny, wet-looking), and supplied with blood (pinkish).

Exploring organs

Your teacher may be able to supply a sheep's heart for you to examine (alternatively, virtual dissections are available). Wear gloves and be careful when using the scalpel.

2. (a) Examine the exterior of the heart. Can you find the features identified top right? Write down the different tissue types you can see and their location:

____

____

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(b) Section the heart through the centre and observe the interior. What tissues can you see now? What is the role of these tissues in the organ? Consult a text or online diagram of the heart if you need help (see BIOZONE's weblinks page).

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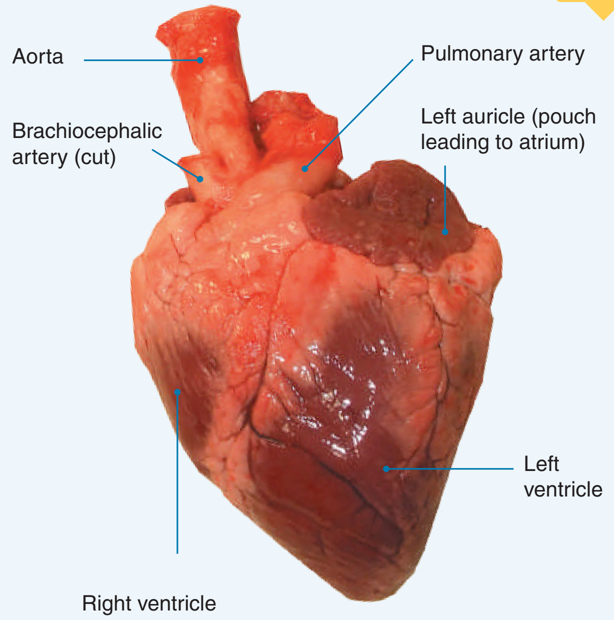
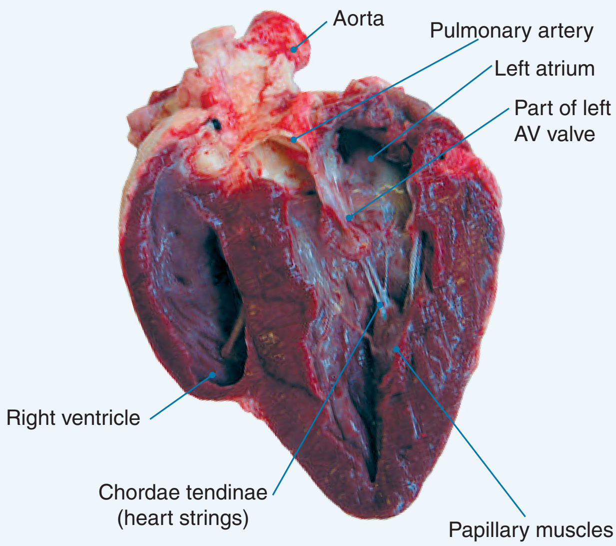
External ventral view of sheep's heart



Frontal section of sheep's heart



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90 Organ Systems Work Together

Key Idea: The circulatory and gas exchange systems interact to provide the tissues with oxygen and remove carbon dioxide.

Circulatory system

Function

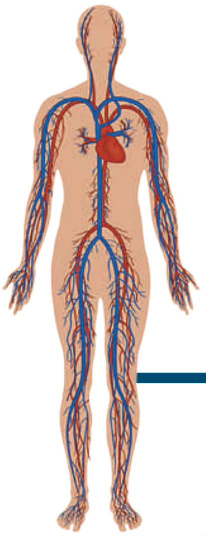
Delivers oxygen (O_2) and nutrients to all cells and tissues. Removes carbon dioxide (CO_2) and other waste products of metabolism. CO_2 is transported to the lungs.

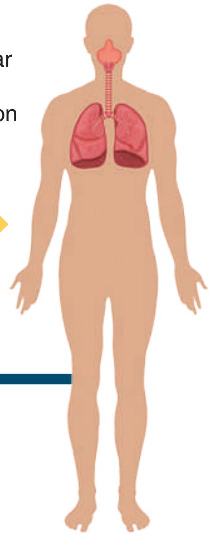
Components

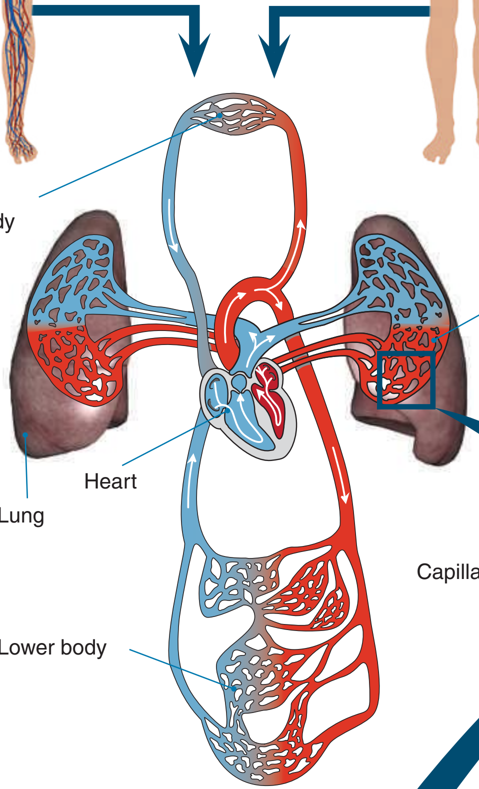
- Heart
- Blood vessels:
  - Arteries
  - Veins
  - Capillaries
- Blood

Interaction between systems

In mammals, the gas exchange (or respiratory) system and cardiovascular system interact to supply oxygen and remove carbon dioxide from the body.







Gas exchange system

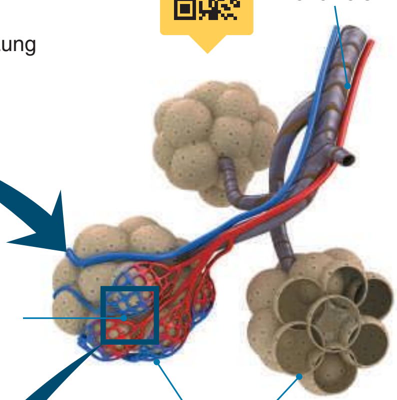
Function

Provides surface for gas exchange. Moves fresh air into and stale air out of the body.

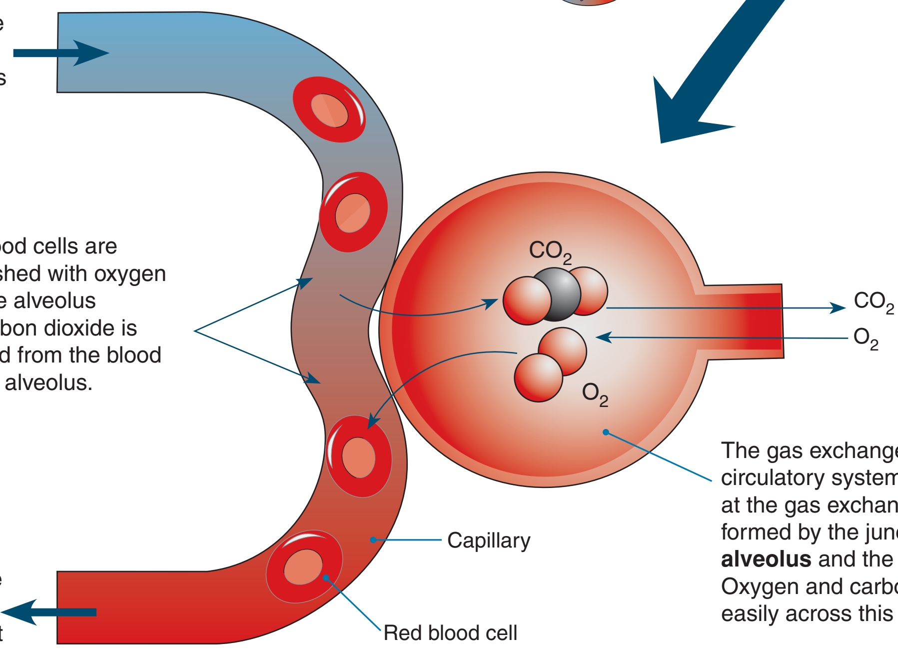
Components

- Airways:
  - Pharynx
  - Larynx
  - Trachea
- Lungs:
  - Bronchi
  - Bronchioles
  - Alveoli
- Diaphragm

Oxygen (O_2) from inhaled air moves from the lungs into the circulatory system and is transported within red blood cells to the heart. The heart pumps the blood to the body where O_2 is released and carbon dioxide (CO_2) is picked up. The blood returns to the heart and is pumped to the lungs where CO_2 is released into the lungs to be breathed out.



The airways of the lungs end at the **alveoli**, the microscopic air sacs that enable gas exchange.



Red blood cells are replenished with oxygen from the alveolus and carbon dioxide is released from the blood into the alveolus.

The carbon dioxide released from the blood exits the body during exhalation. Inhalation brings in fresh air, containing oxygen.

The gas exchange system and the circulatory system come together at the gas exchange membrane formed by the junction of the **alveolus** and the **capillary wall**. Oxygen and carbon dioxide diffuse easily across this thin barrier.

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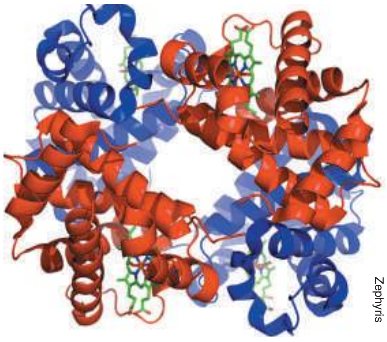
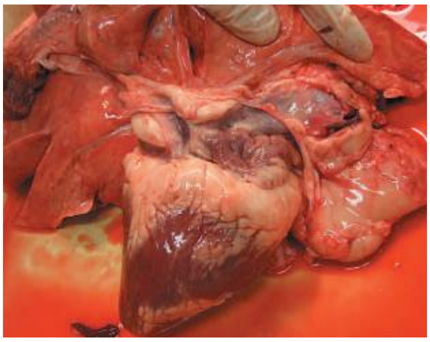
The response to exercise shows the close link between the circulatory and gas exchange systems. During exercise, breathing rate increases to provide more oxygen, which is carried by the blood to supply respiration (ATP generation) in working muscles. Heart rate increases to increase the rate at which oxygen is delivered to the tissues and carbon dioxide is returned to the lungs.



Oxygen is transported in red blood cells by the protein haemoglobin (above). In the capillaries of the lungs (high oxygen), haemoglobin binds oxygen tightly. In the tissues, higher carbon dioxide levels cause haemoglobin to release its oxygen. CO_2 is carried in the blood as bicarbonate ($CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^-$). In the lungs, this dissociates back into CO_2 and water.



As with all organ systems, the circulatory and gas exchange systems are interdependent. Organs in the circulatory system (e.g. the heart) need oxygen to keep working and this is supplied by the lungs. If the heart were to stop beating it and all other organs would quickly run out of oxygen. Similarly, if breathing were to stop, all organs would quickly run out of oxygen.

1. (a) What happens to the rate of blood flow during exercise? ____________________

   (b) What happens to the breathing rate during exercise? ____________________

   (c) How do the circulatory and gas exchange systems interact to accommodate the extra oxygen requirements of an exercising person?

2. Lung diseases affect rates of gas exchange in the lung. Suggest how this would affect the body: ____________________

3. (a) At which point in the body do the respiratory and circulatory systems directly interact? ____________________

   (b) Explain what is happening at this point: ____________________

4. In your own words, describe how the circulatory system and respiratory system work together to provide the body with oxygen and remove carbon dioxide:

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91 Stem Cells, Ethics, and Bioartificial Organs

Key Idea: Using animals in scientific and medical research helps to understand and test new theories and medicines, but must be done in a way that minimises animal discomfort.

The use of animals in scientific research has played a vital role in many advances in science and medicine. Animals (often specially bred rats or mice) are used as models of how a human system might work and are the basis for preliminary research that might later be applied to humans. This includes developing theories and processes around stem cells and developing and using bioartificial organs. During this research, there is the chance that some of these animals may experience harm. How much depends greatly on the way they are treated and the research involved. Many countries have strict guidelines as to when and how animals can be used in research. These are often based around the 3Rs principle of replacement, reduction, and refinement.

The 3Rs of ethical research

The 3Rs are guiding principles for the use of animals in research, testing, and teaching. Animals should only be used when there are no alternatives, any harm must be measured against the benefits, and those harms must be minimised.

- **Replacement**: Can animals be replaced in the research? In many cases computer modelling can produce highly accurate results and can easily be used to identify unforeseen problems and refine tests. This reduces the need for animal testing, so that it occurs in the latter stages of the research (if at all).
- **Reduction**: Only the minimum number of animals needed to produce reliable or statistically significant data should be used.
- **Refinement**: Investigations should be reviewed to identify where the number of animals used could be reduced. This information can then be applied to refining subsequent investigations.

Stem cells, bioartificial organs and ethics

- Bioartificial organs are grown using a scaffold implanted with stem cells. These are cultured to grow and differentiate around the scaffold to produce a functional three dimensional organ (or part of an organ). Currently only simple organs or sections of organs can be grown but research is constantly producing new developments (e.g. new materials and techniques).
- Ethical issues can arise from this kind of research. Often animals are used to practice and develop techniques and this can cause them considerable distress (see below).

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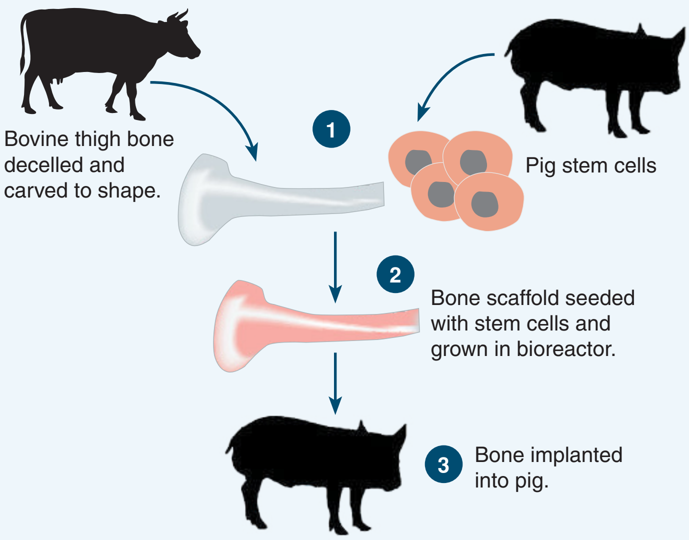
Engineered vascular tissue (blood vessel). The scaffold can be seen supporting the outer cells.

Using bioartificial tissue to replace a jaw

Bones can be replaced using titanium but this means a loss of bone marrow, which plays an important role in the body. In 2016, researchers began trials on growing new bone for transplant.

- The experiment was carried out on Yucatan miniature pigs because the jaw structure is similar to humans. The researchers took part of a cattle thigh bone and removed all the cells and tissue, leaving just the bone structure. They then carved the bone into the shape of part of the pig mandible.
- This bone scaffold was seeded with pig stem cells and placed into a bioreactor. The cells developed into bone cells and grew into and around the scaffold (this took about 3 weeks). The matching part of the pig mandible was removed and the bioartificial jawbone implanted.
- Six months later the implants had fully grafted and the pigs were able to use their jaw normally.



1. As a group discuss why the experiment on pigs jaws above was carried out and its pros and cons. Discuss likely ethical issues in relation to the pigs and if you think the experiment was worth carrying out. Summarize your discussion below:

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SHE

92 KEY TERMS AND IDEAS: Did You Get It?

1. Test your vocabulary by matching each term to its definition, as identified by its preceding letter code.

multipotent	A	A type of cell that possesses the qualities of self renewal and potency.
pluripotent	B	Ability to divide many times while maintaining an undifferentiated state.
self renewal	C	Able to give rise to any cells of the body, except extra-embryonic cells.
stem cell	D	The initial cell formed from the union of two gametes.
potency	E	Able to give rise a limited number of cell types, related to their tissue of origin.
zygote	F	Ability to differentiate into specialised cell types.

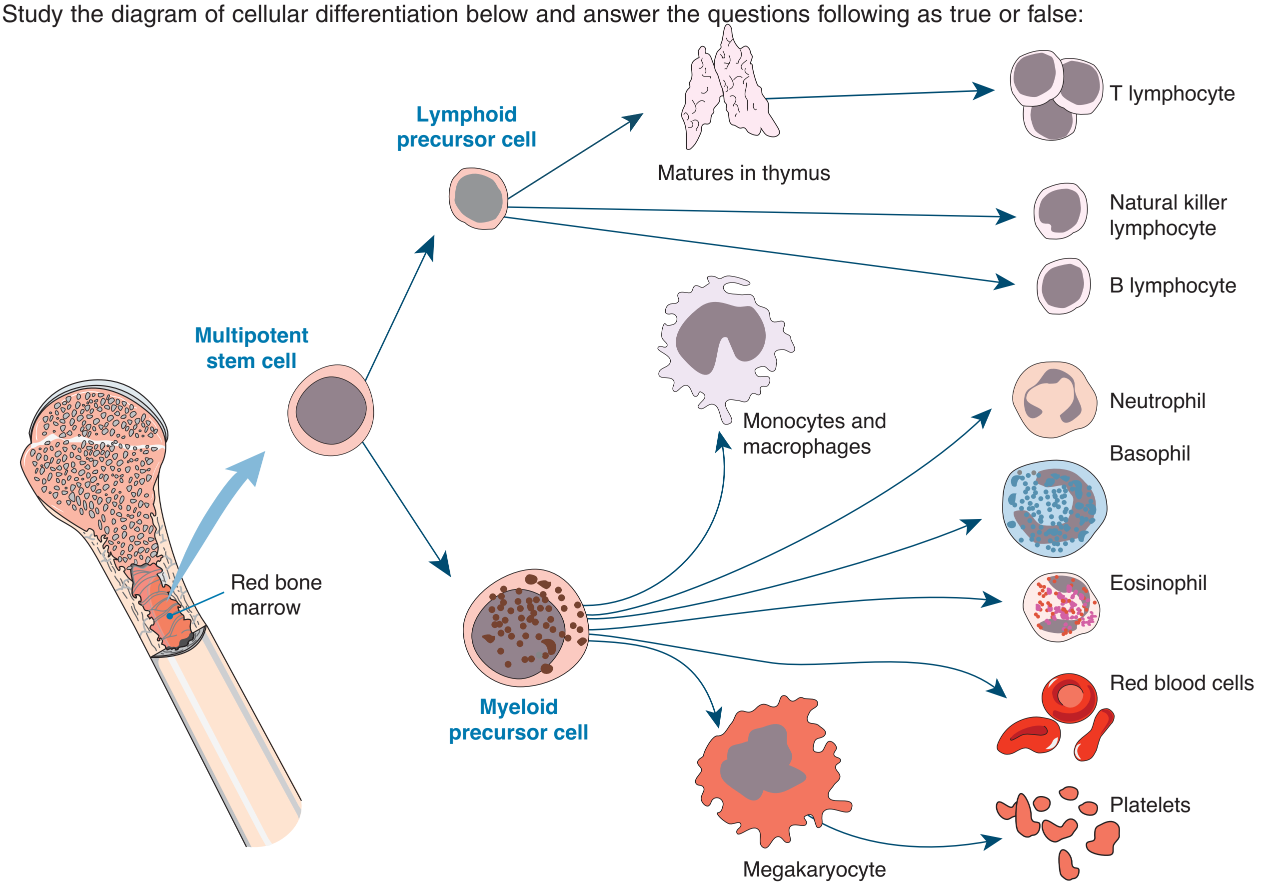
2. Give an example of each of the following stem cell types:

(a) Multipotent: ______

(b) Pluripotent: ______

(c) Totipotent: ______

3. Study the diagram of cellular differentiation below and answer the questions following as true or false:



(a) T lymphocytes can differentiate from a haematopoietic multipotent stem cell: ______

(b) Lymphoid precursor cells can produce red blood cells: ______

(c) Neutrophils mature from myeloid precursor cells: ______

4. (a) What is the link between cells, tissues, and organs? ______

______

(b) How do tissues improve functional efficiency? ______

______

______

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UNIT 1
Topic 2

Gas Exchange and Transport

Key terms

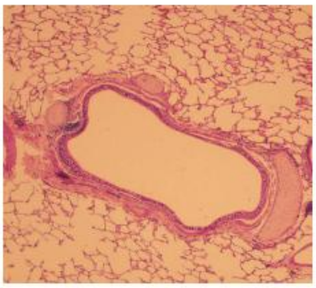
alveoli
Bohr effect
bronchi
cellular respiration
countercurrent exchange
diffusion
gas exchange membrane
gills
haemoglobin
lungs
oxygen-haemoglobin dissociation curve
respiratory gas
trachea

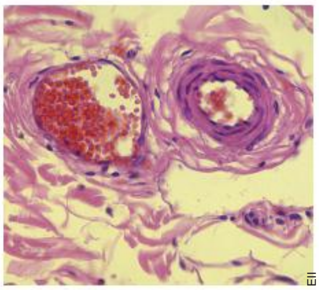
Activity number

Gas exchange surfaces

Key skills and knowledge

- ☐ 1 Distinguish between cellular respiration and gas exchange and explain why organisms must exchange respiratory gases with their environment and why they need specialised gas exchange surfaces. Recall the raw materials and waste products of cellular respiration. **93**
- ☐ 2 Describe the structural features of gas exchange surfaces. Recall the significance of surface area : volume ratio to the exchange of materials, such as respiratory gases, with the environment. **93**
- ☐ 3 With reference to alveoli and gills, explain the relationship between the structural features you have identified and the function of gas exchange surfaces. **93**
- ☐ 4 Understand the constraints that environment (air versus water) places on gas exchange, including reference to internalisation of systems and the presence of countercurrent exchange mechanisms to maximise exchange rates across the gas exchange surface. **93 94**





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Gas exchange and transport

Key skills and knowledge

- ☐ 5 Describe the basic structure and function of gills in fish, including reference to countercurrent exchange and its role in increasing oxygen uptake along the gill. **94**
- ☐ 6 Describe the gross structure of the human gas exchange system, explaining how the cells, tissues, and organs function together to exchange respiratory gases between the blood and the environment. **95 96**
- ☐ 7 In more detail than #2 above, describe the gas exchange membrane formed by the physical arrangement of the alveolar epithelium and the epithelium of the capillary. **96**
- ☐ 8 Explain how respiratory gases move across the gas exchange membrane. Use data presented in diagrams and schematics to predict the direction in which materials will be exchanged between the alveoli and capillaries and between the capillaries and the tissues of the body (e.g. muscle, organs). **96 97 99 100**
- ☐ 9 Recognise differences in the structure and function of blood vessels in mammals, including arteries, veins, and capillaries. Understand the importance of capillary networks (beds) as exchange surfaces. **98 99**

Gas transport in mammals

Key skills and knowledge

- ☐ 10 Describe the nature and role of blood and the protein haemoglobin (Hb) in vertebrate internal transport systems. Understand that oxygen and carbon dioxide are transported in the blood between the tissues and the gas exchange surface. **97**
- ☐ 11 Describe the role of haemoglobin and red blood cells in the transport of oxygen in mammals. Interpret the oxygen-haemoglobin dissociation curve in terms of cooperative binding and the Bohr effect. **97**

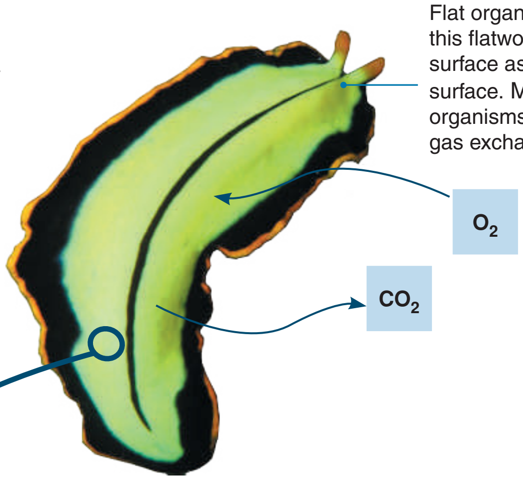
93 Gas Exchange

Key Idea: Animal gas exchange systems are suited to the animal's environment, body form, and metabolic needs.

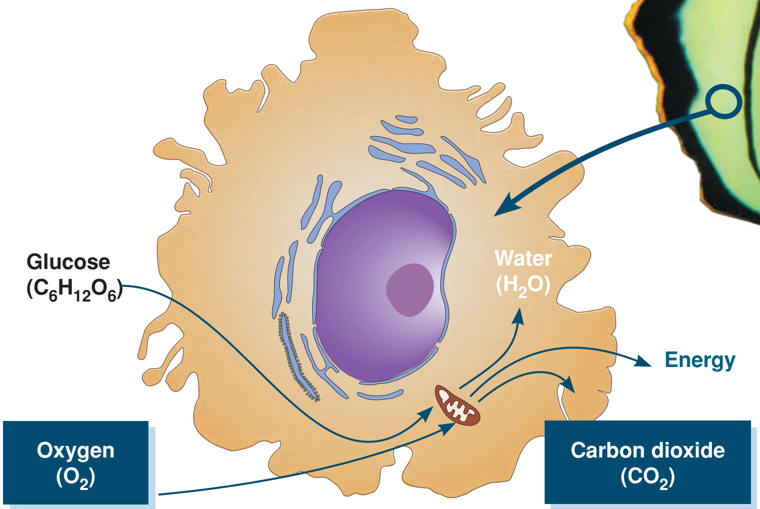
To meet the demands of aerobic metabolism, organisms must exchange gases with the environment. Some organisms can exchange gases directly across their body surface, but most organisms have specialised gas exchange systems adapted to function in their specific environment. The type and complexity of the exchange system reflects the demands of metabolism for gas exchange (oxygen delivery and carbon dioxide removal) and the environment (aquatic or terrestrial).

Cellular respiration and gas exchange are linked

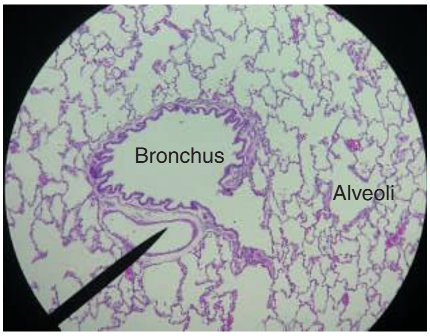
Recall that cellular respiration takes place in the mitochondria of every cell in the body. Glucose is broken down to harness energy as ATP. It creates a constant demand for oxygen (O_2) and a need to eliminate carbon dioxide gas (CO_2). These gases are delivered and removed via diffusion across gas exchange surfaces.

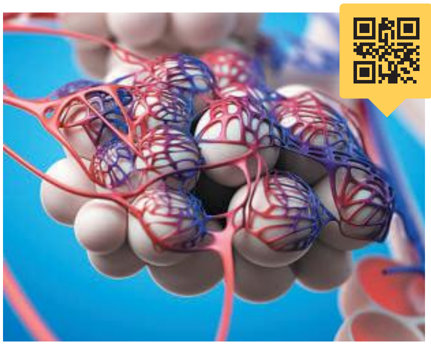


Flat organisms, such as this flatworm, use the body surface as the gas exchange surface. Most multicellular organisms have specialised gas exchange systems.



Gas exchange is the process by which gases enter and leave the body by diffusion across gas exchange surfaces. To achieve effective gas exchange rates, gas exchange surfaces are thin with a high surface area. They are moist because gases must dissolve before diffusing across. In animals with gas exchange systems, the gas exchange surfaces lie close to capillary networks, and respiratory gases enter and leave the circulatory fluid by diffusion.





Blood cells within a capillary. The blood carries O_2 and CO_2

In mammalian lungs, the alveoli (microscopic air sacs) provide a large surface area for gas exchange. The walls of the alveoli are only one cell thick (tissue section above) and are enveloped by capillaries (model, centre). Respiratory gases move across the gas exchange surface by diffusion. Effective gas exchange relies on maintaining a concentration gradient for gas diffusion. Oxygen is transported away from the gas exchange surface by the blood (above right), reducing its concentration relative to the environmental side of the gas exchange surface. CO_2 is transported to the gas exchange surface, increasing its concentration relative to the environmental side of the membrane. It then diffuses out of the blood, across the membrane, and into the external environment.

1. What is the purpose of gas exchange? ______________________________

____

2. How are gases exchanged with the environment? ______________________________

3. How are gradients for diffusion maintained in a simple organism (one without a gas exchange system)? ______________________________

____

4. How are gradients for diffusion maintained in an organism with a gas exchange system? ______________________________

____

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Gas exchange systems and environment

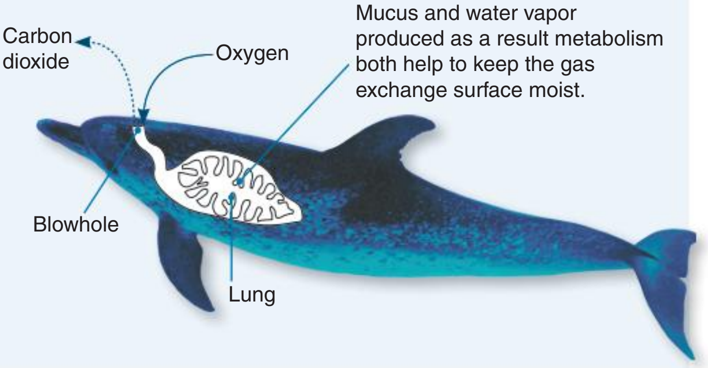
The way an animal exchanges gases with its environment is influenced by the animal's body form and by the environment in which the animal lives. Small or flat organisms in moist or aquatic environments, such as sponges and flatworms, require no specialised structures for gas exchange. Larger or more complex animals have specialised systems to supply the oxygen to support their metabolic activities. The type of environment presents different gas exchange challenges to animals. In air, gas exchange surfaces will dry out. In water, the oxygen content is much lower than in air.

Simple organisms

The high surface area to volume ratio of very flat or very small organisms, such as this nematode, enables them to use the body surface as the gas exchange surface.

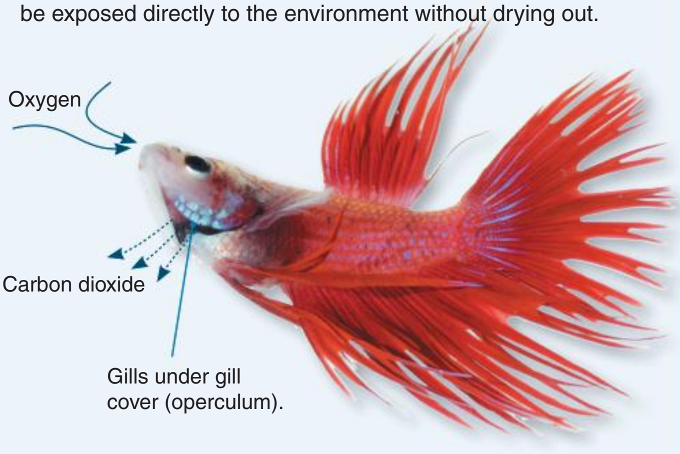
Air breathing vertebrates

The gas exchange surface in mammals and other air breathing vertebrates is located in internal lungs. Their internal location within the body protects the lungs from the dry environment of the air and keeps the exchange surfaces moist. The many alveoli of the lungs provide a large surface area to maximise gas exchange rates. Exchange rates for the diffusion of gases are maintained by ventilation of the gas exchange surface (breathing in and out).



Bony fish, sharks, and rays

Fish extract oxygen dissolved in water using **gills**. Gills achieve high extraction rates of oxygen from the water. This is important because water contains only 1% dissolved oxygen by volume, whereas air (at sea level) is 21% oxygen. Bony fish ventilate the gill surfaces by movements of the gill cover. The water supports the gills, and the gill lamellae (the gas exchange surface) can be exposed directly to the environment without drying out.



5. Describe two reasons why most animals require specialised gas exchange structures and systems:

   (a) ______________________________

   ____

   ____

   (b) ______________________________

   ____

   ____

6. Describe three ways the gas exchange surfaces of air breathers are kept moist:

   (a) ______________________________

   ____

   (b) ______________________________

   ____

   (c) ______________________________

   ____

7. Explain why gills would not work in a terrestrial environment:

   ____

   ____

   ____

   ____

   ____

8. Why do animals have to ventilate their gas exchange surfaces:

   ____

   ____

   ____

9. Describe a difficulty associated with gas exchange:

   (a) In air: ______________________________

   ____

   ____

   (b) In water: ______________________________

   ____

   ____

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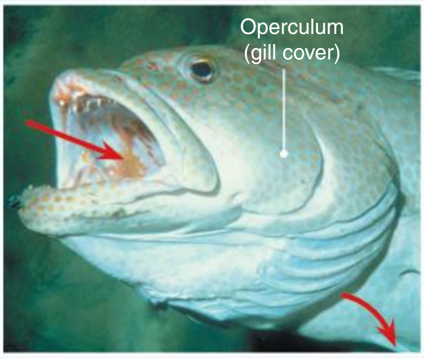
94 Gas Exchange in Fish

Key Idea: Fish gills are thin, vascular structures just behind the head. Countercurrent flow enables efficient exchange of gases between the water and the blood in the gill capillaries.

Fish obtain the oxygen they need from the water using **gills**, which are membranous structures supported by cartilaginous or bony struts. As water flows over the gill surface, respiratory gases are exchanged between the blood and the water. In fish, high oxygen extraction rates are achieved using countercurrent exchange and by pumping water across the gill surface (most bony fish) or swimming continuously with the mouth open (called ram ventilation, seen in sharks, rays, and some bony fish, e.g. tuna).

Fish gills

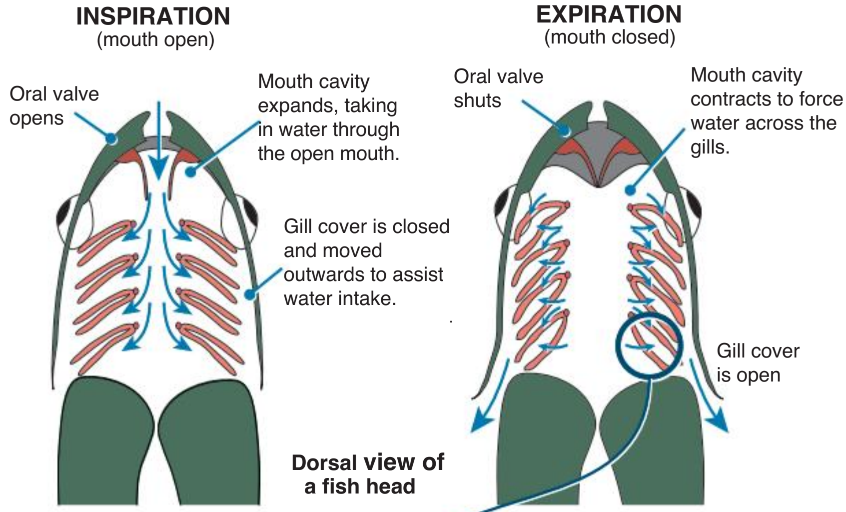
The gills of fish are very thin, filamentous structures, with individual filaments supported and kept apart from each other by the water. This gives them a high surface area for gas exchange. The outer surface of the gill is in contact with the water, and blood flows in vessels inside the gill. Gas exchange occurs by diffusion between the water and blood across the gill membrane and capillaries. The operculum (gill cover) permits exit of water and acts as a pump, drawing water past the gill filaments. The gills of fish are very efficient and achieve an 80% extraction rate of oxygen from water; over three times the rate of human lungs from air.



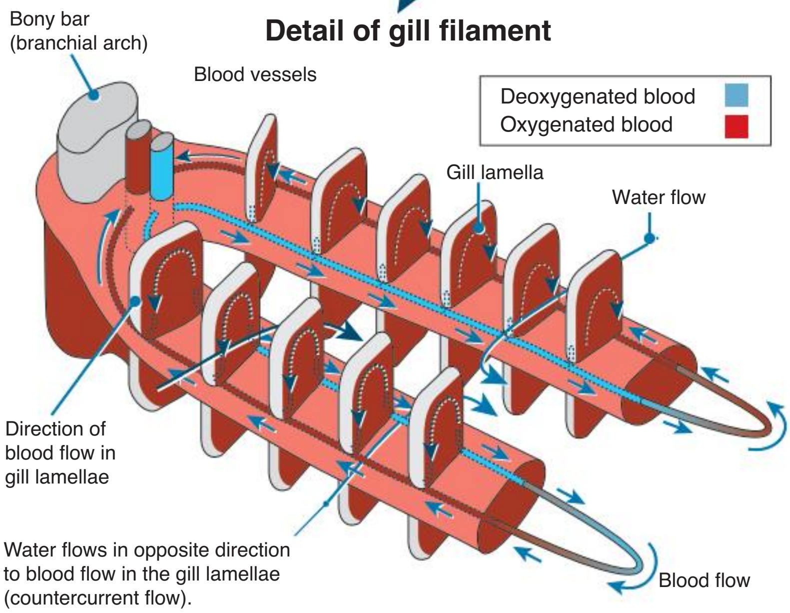
Ventilation of the gills

Most bony fish ventilate the gills by opening and closing the mouth in concert with opening and closing the operculum. The mouth opens, increasing the volume of the buccal (mouth) cavity, causing water to enter. The operculum bulges slightly, moving water into the opercular cavity. The mouth closes and the operculum opens and water flows out over the gills. These pumping movements keep oxygenated water flowing over the gills, maintaining the concentration gradient for diffusion. Other fish (e.g. sharks and tuna) must swim continuously to achieve the same gill ventilation.

Breathing in bony fish



Detail of gill filament



Source: C.J. Clegg & D.G. McKean (1994)

1. Describe three features of a fish gas exchange system (gills and related structures) that facilitate gas exchange:

(a) ______________________________

(b) ______________________________

(c) ______________________________

2. Describe how fish achieve adequate ventilation of the gills through:

(a) Pumping (mouth and operculum): ______________________________

____

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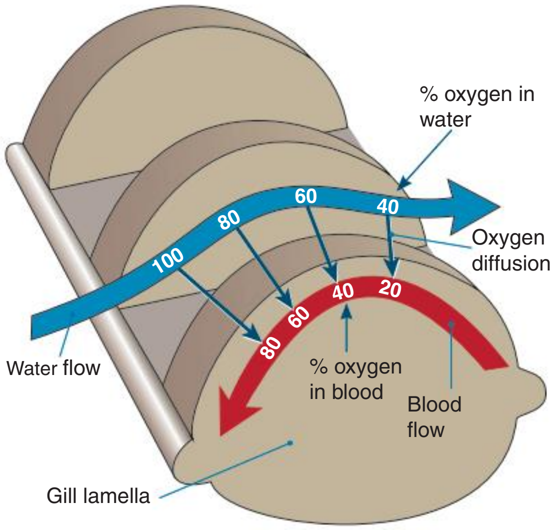
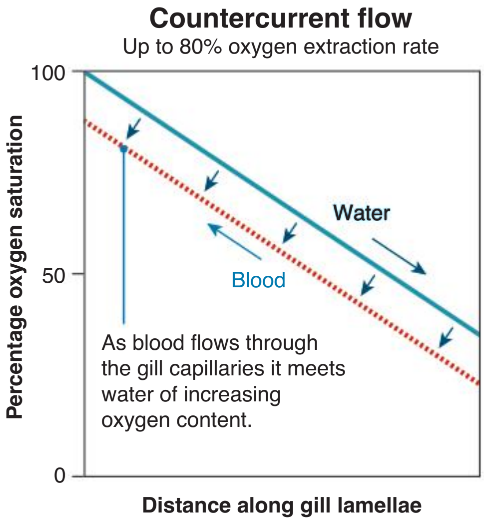
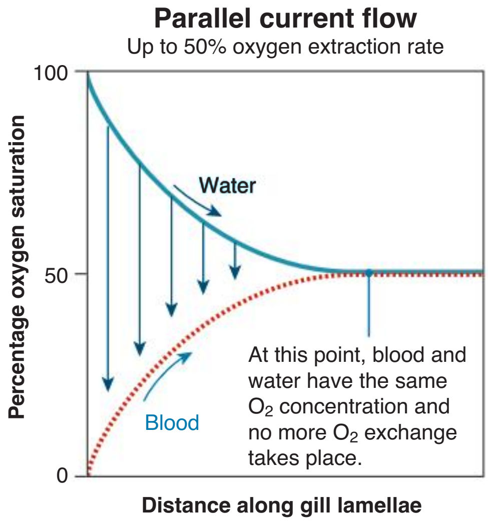
Countercurrent flow

- The structure of fish gills and their physical arrangement in relation to the blood flow maximises gas exchange rates. A constant stream of oxygen-rich water flows over the gill filaments in the opposite direction to the blood flowing through the gill filaments.
- This is called countercurrent flow (right and below left) and it is an adaptation for maximising the amount of oxygen removed from the water. Blood flowing through the gill capillaries encounters water of increasing oxygen content. The concentration gradient (for oxygen uptake) across the gill is maintained across the entire distance of the gill lamella and oxygen continues to diffuse into the blood (CO_2 diffuses out at the same time).
- A parallel current flow (below, far right) could not achieve the same oxygen extraction rates because the concentrations across the gill would quickly equalise).







(b) Continuous swimming (mouth open): ____________________

3. Describe countercurrent flow: ____________________

4. (a) How does the countercurrent system in a fish gill increase the efficiency of oxygen extraction from the water?

(b) Explain why parallel flow would not achieve the same rates of oxygen extraction: ____________________

5. Warmer water holds less oxygen than colder water. Given this, suggest why many fish are very sensitive to increases in water temperature:

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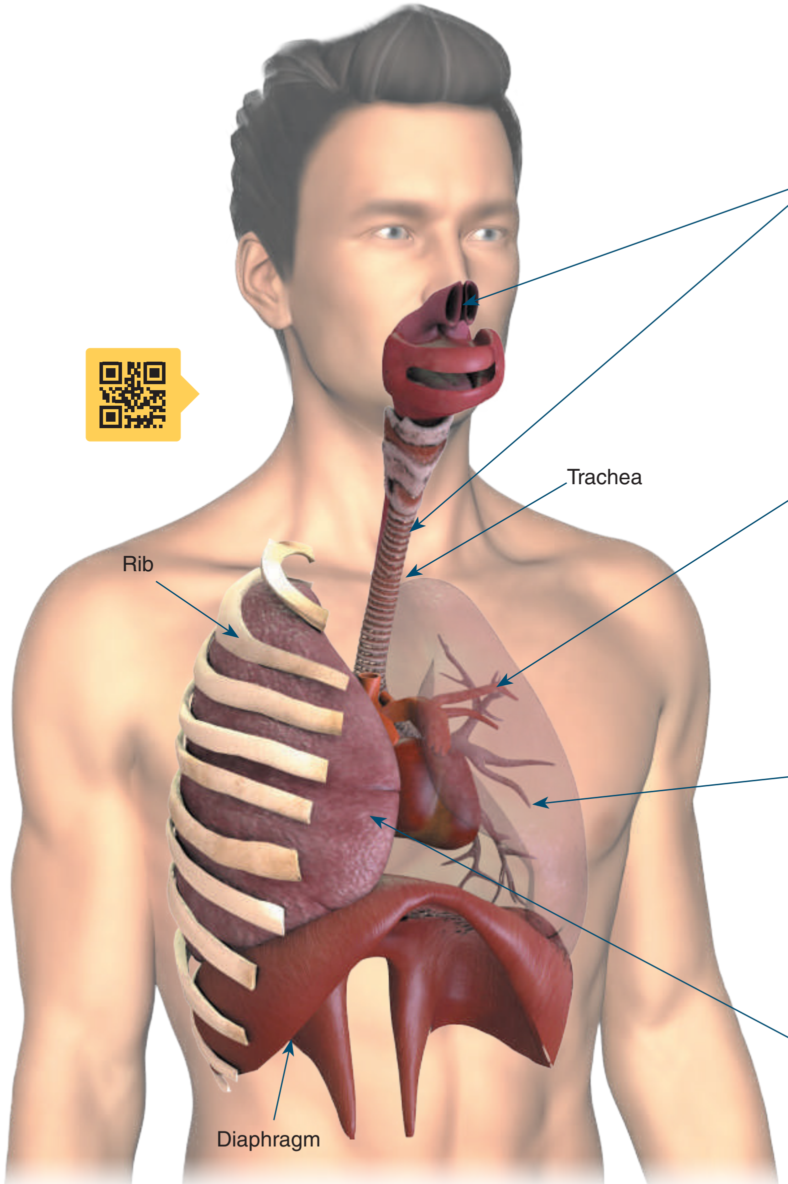
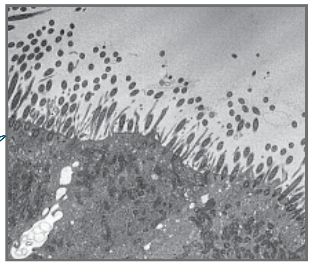
95 The Human Gas Exchange System

Key Idea: The tissues and organs of the human gas exchange work together to enable the exchange of gases between the body's cells and the environment.

The gas exchange system consists of the passages of the mouth and nose, the trachea, and the tubes and air sacs of the lungs. Cooperation with the muscles of the diaphragm and ribcage contribute to its function. Each region is specialised to perform a particular role in the organ system's overall function, which is to exchange respiratory gases (O_2 and CO_2) between the body's cells and the environment.





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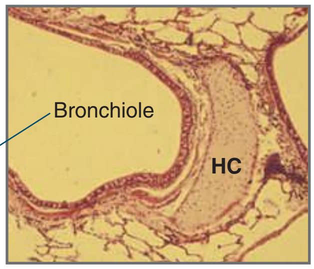
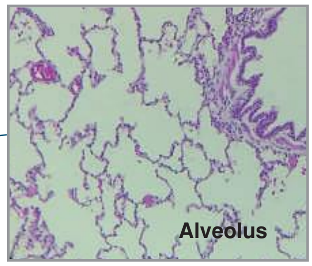
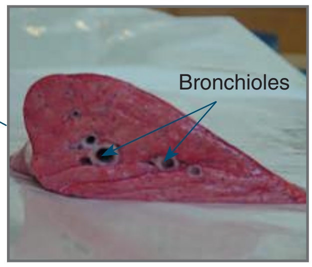
Goblet cells in the nasal cavity produce mucus, which traps dust particles. Ciliated epithelial cells sweep the mucus towards the throat (pharynx) where it is swallowed. The trachea is also lined with goblet cells and ciliated epithelium.



Rings of hyaline cartilage (HC) provide support for the trachea, bronchi, and the larger bronchioles.



The lungs contain air spaces surrounded by alveolar epithelial cells (pneumocytes), forming alveoli (air sacs), where gas exchange takes place. The alveoli receive air from tubes, called bronchioles.



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The **lungs** have a soft, spongy texture made up of the epithelium of the alveoli. Bronchioles form a network of small tubes to transport gases to and from the alveoli. The larger bronchioles are supported by connective tissue (e.g. cartilage).

1. Name three types of cells in the respiratory system and their function:

   (a) ____

   ____

   (b) ____

   ____

   (c) ____

   ____

2. What is the primary organ of gas exchange? ______________________

3. Which cells form the alveoli? ______________________

4. What is the purpose of the hyaline cartilage in the gas exchange system? ______________________

____

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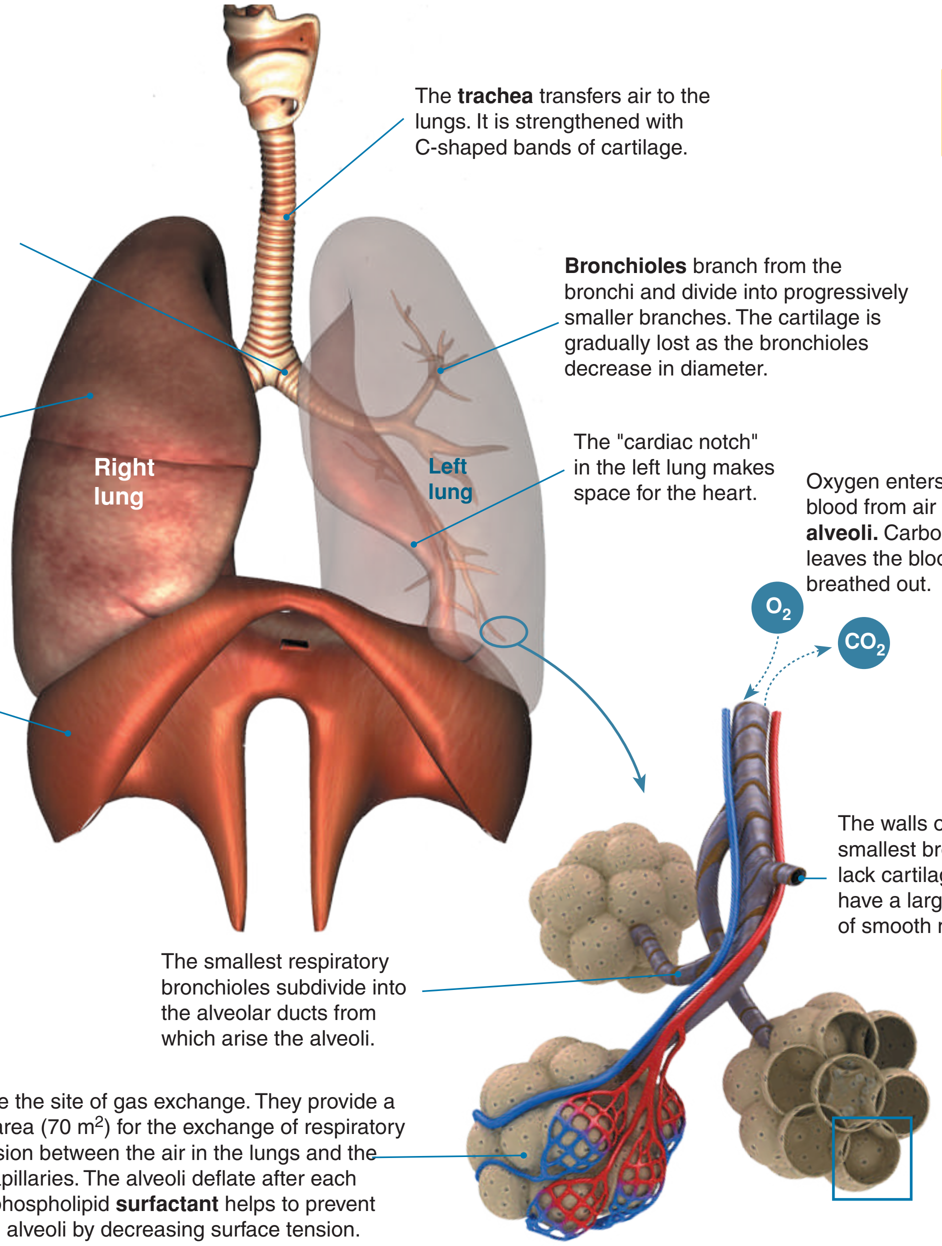
96 The Lungs

Key Idea: Lungs are internal sac-like organs connected to the outside by a system of airways. The smallest airways end in thin-walled alveoli, where gas exchange occurs.

The respiratory system includes all the structures associated with exchanging respiratory gases with the environment. In mammals, the gas exchange organs are paired lungs connected to the outside air by way of a system of tubular passageways: the trachea, bronchi, and bronchioles.



Alveolar cross section at top of next page

1. What is the purpose of the trachea, bronchi, and bronchioles? ______________________

____

2. What is the purpose of the diaphragm? ______________________

____

3. (a) Explain how the basic structure of the human gas exchange system provides such a large area for gas exchange:

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(b) In what region of the lung does the actual exchange of gases take place? ______________________

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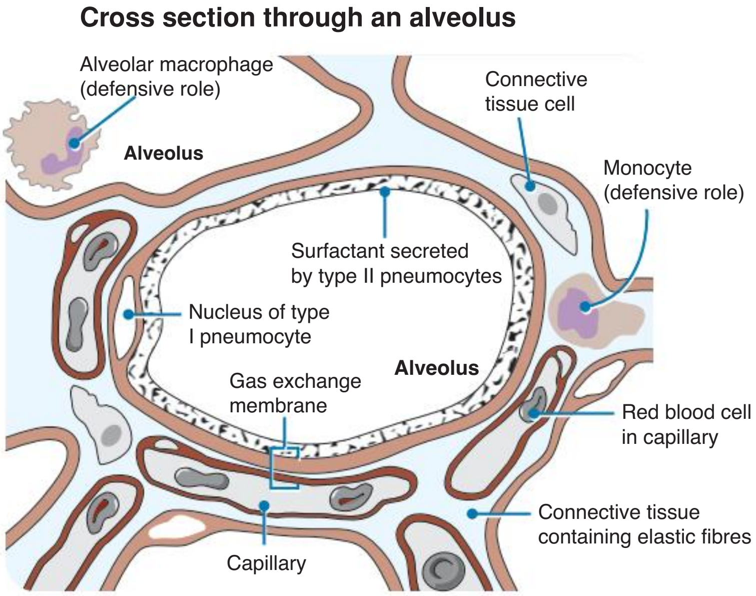

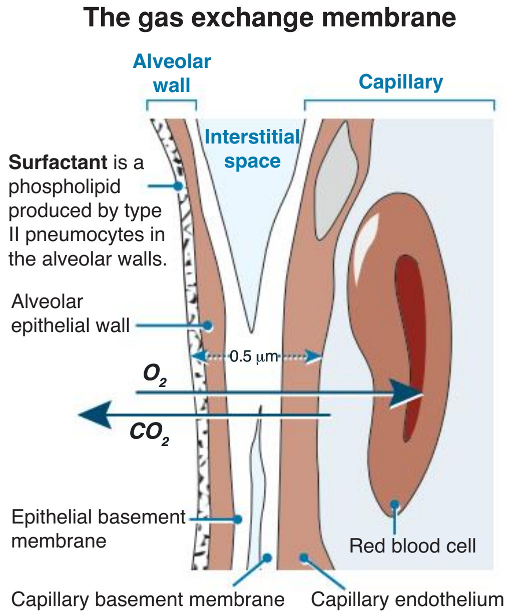

Above: The physical arrangement of the alveoli to the capillaries through which the blood moves. The alveolus is lined with **pneumocytes** (alveolar epithelial cells). Phagocytes (monocytes and macrophages) are present to protect the lung tissue. Elastic connective tissue gives the alveoli their ability to expand and recoil.

The **gas exchange membrane** is the layered junction between the alveolar epithelial cells, the endothelial cells of the capillary, and their associated basement membranes (thin connective tissue layers under the epithelia). Gases move freely across this membrane.

4. Describe the structure and purpose of the alveolar-capillary (gas exchange) membrane: ______________________

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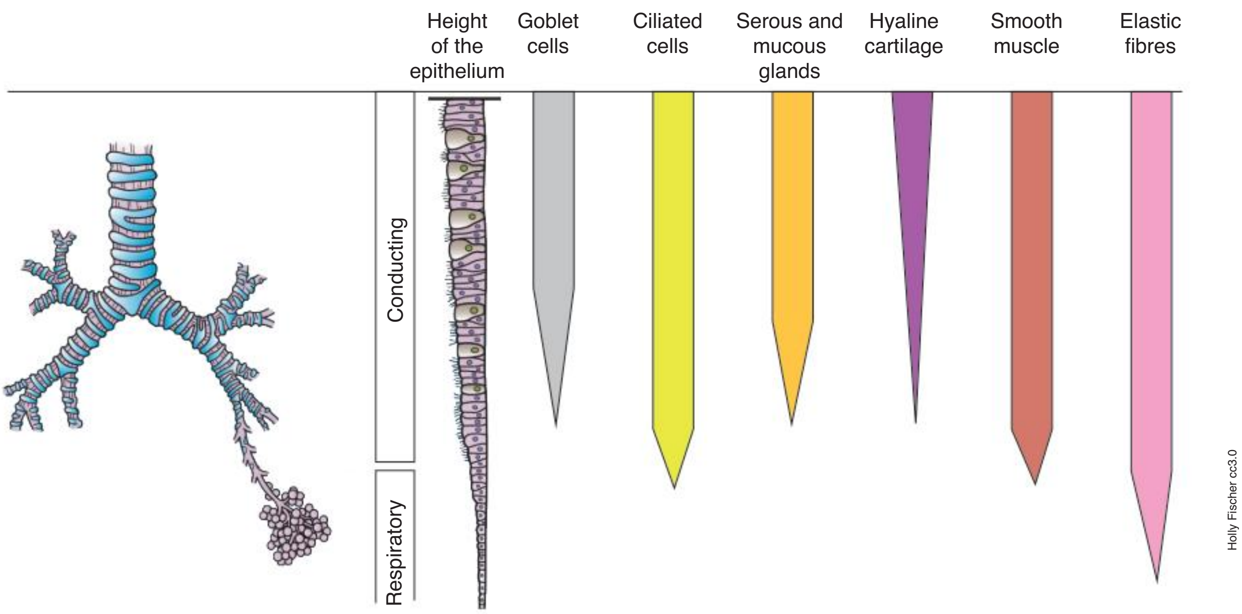
____

5. The diagram below shows the different types of cells and their positions and occurrence in the lungs. Use it to answer the following questions:



(a) Why does the epithelium become very thin in the respiratory zone? ______________________

____

____

(b) Why would elastic fibres be present in the respiratory zone, whereas hyaline cartilage is not? ______________

____

____

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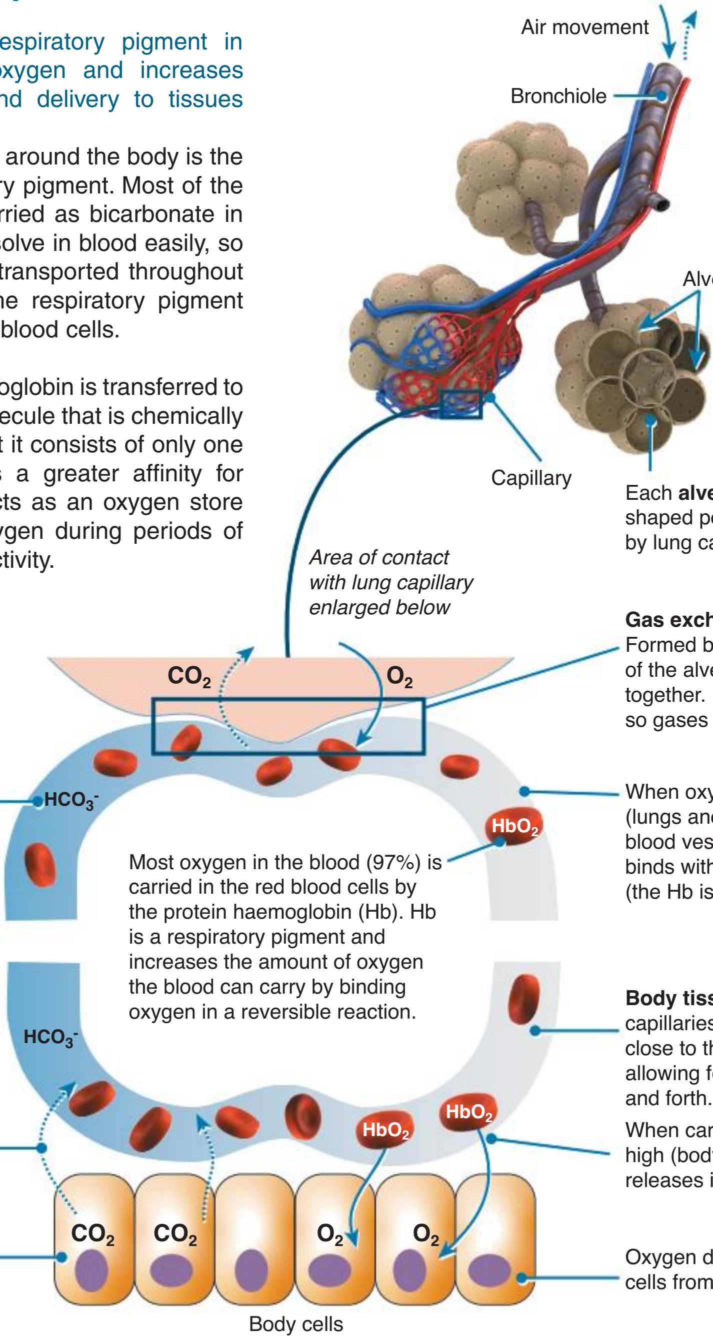
97 Gas Transport in Humans

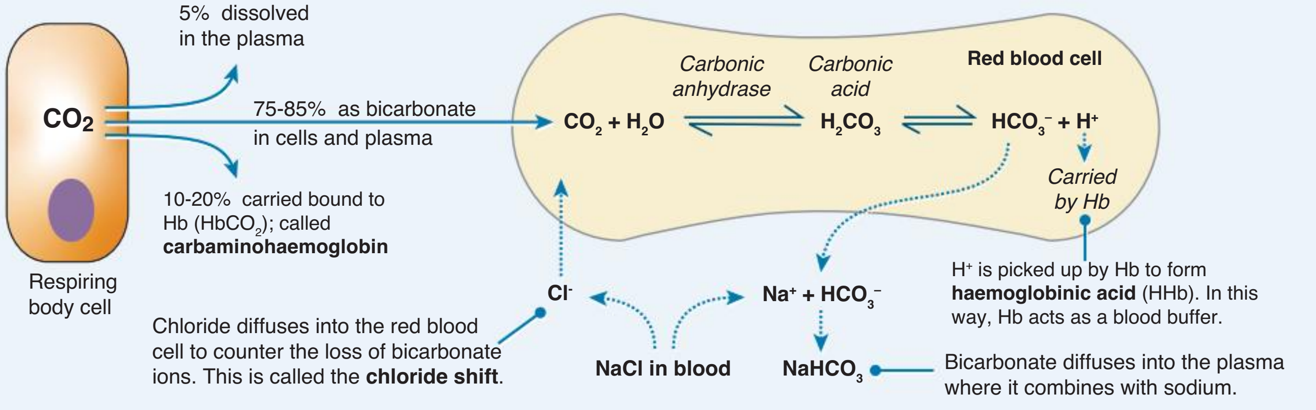
Key Idea: Haemoglobin is a respiratory pigment in red blood cells, which binds oxygen and increases the efficiency of its transport and delivery to tissues throughout the body.

The transport of respiratory gases around the body is the role of the blood and its respiratory pigment. Most of the carbon dioxide in the blood is carried as bicarbonate in the plasma. Oxygen does not dissolve in blood easily, so in vertebrates, e.g. humans, it is transported throughout the body chemically bound to the respiratory pigment **haemoglobin** (Hb) inside the red blood cells.

In the muscles, oxygen from haemoglobin is transferred to and retained by **myoglobin**, a molecule that is chemically similar to haemoglobin except that it consists of only one heme-globin unit. Myoglobin has a greater affinity for oxygen than haemoglobin and acts as an oxygen store within muscles, releasing the oxygen during periods of prolonged or extreme muscular activity.



Transport of carbon dioxide in the blood



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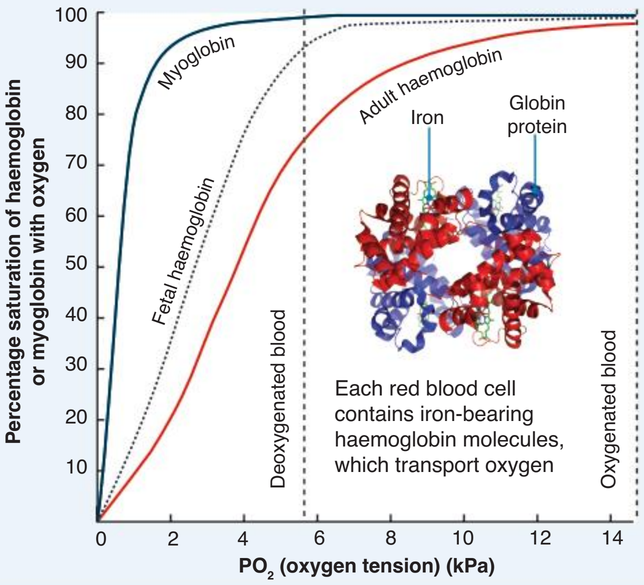
Respiratory pigments and the transport of oxygen

Fig.1: Dissociation curves for haemoglobin and myoglobin at normal body temperature for fetal and adult human blood.



- The most important factor determining how much oxygen is carried by haemoglobin (Hb) is the level of oxygen in the blood. The greater the oxygen tension, the more oxygen will combine with Hb.
- This relationship can be illustrated in an **oxygen-haemoglobin dissociation curve** (left). In the lung capillaries (high O_2), a lot of oxygen is picked up and bound by Hb. In the tissues (low O_2), oxygen is released.
- Myoglobin in skeletal muscle has a very high affinity for oxygen and will take up oxygen from Hb in the blood. It can therefore act as an oxygen store.
- Fetal Hb has a high affinity for oxygen and carries 20-30% more than maternal Hb.
- The release of oxygen to the tissues is enhanced by the effect of pH. As pH increases (lower CO_2), more oxygen combines with Hb. As the blood pH decreases (higher CO_2), Hb binds less oxygen and releases more to the tissues. This is called the Bohr effect.

1. (a) Identify two regions in the body where oxygen levels are relatively high: ______________________

   (b) Identify two regions where carbon dioxide levels are relatively high: ______________________

2. (a) What is the function of haemoglobin? ______________________

   (b) Explain the significance of the reversible binding of oxygen by haemoglobin: ______________________

3. (a) How is haemoglobin saturation affected by the oxygen level in the blood? ______________________

   (b) What is the significance of this relationship to oxygen delivery to the tissues? ______________________

4. At low blood pH, less oxygen is bound by haemoglobin and more is released to the tissues:

   (a) Name this effect: ______________________

   (b) What is its significance? ______________________

5. (a) Compare the affinity of myoglobin and haemoglobin for oxygen: ______________________

   (b) Why is the very high affinity of myoglobin for oxygen important? ______________________

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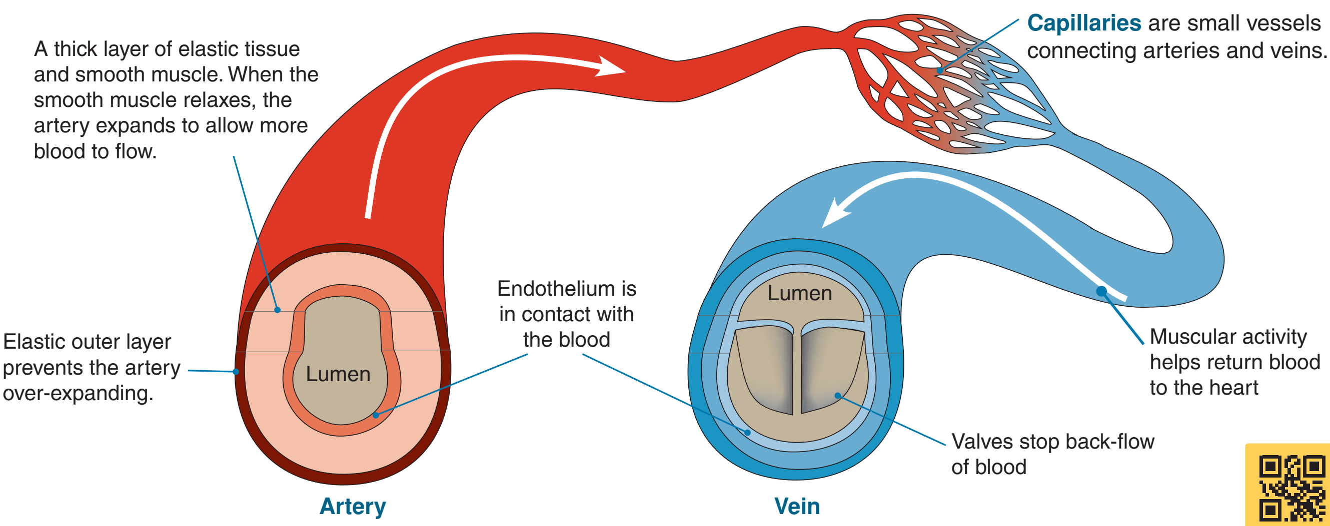
98 Blood Vessels

Key Idea: The blood vessels of the circulatory system connect the body's cells to the organs that exchange gases, absorb nutrients, and dispose of wastes.

In vertebrates, **arteries** are the blood vessels that carry blood away from the heart to the capillaries within the tissues. The large arteries that leave the heart divide into medium-sized (distributing) arteries. Within the tissues and organs, these distributing arteries branch to form **arterioles**, which deliver blood to capillaries. Blood flow to the tissues is altered by contraction (**vasoconstriction**) or relaxation (**vasodilation**) of the blood vessel walls. Vasoconstriction increases blood pressure whereas vasodilation has the opposite effect. **Veins** are the blood vessels that return blood to the heart from the tissues. The smallest veins (**venules**) return blood from the capillaries to the veins. Veins and their branches contain about 59% of the blood in the body. The structural differences between veins and arteries are mainly associated with differences in the relative thickness of the vessel layers and the diameter of the lumen (space within the vessel). These, in turn, are related to the vessel's functional role.



Arteries

Arteries have an elastic, stretchy structure that enables them to withstand and maintain the high pressure of blood being pumped from the heart. At the same time, their ability to contract (a feature of the central muscle layer) helps regulate blood flow and pressure.

Arteries nearer the heart have more elastic tissue to resist the higher pressures of the blood leaving the left ventricle. Arteries further from the heart have more muscle to help them maintain blood pressure. Between heartbeats, the elastic walls of the artery recoil, maintaining an even pressure despite the pulsing nature of blood flow.

Veins

Veins are made up of the same three layers as arteries but they have less elastic and muscle tissue, a relatively thicker external layer, and a larger, less defined lumen.

Although veins are less elastic than arteries, they can still expand enough to adapt to changes in the pressure and volume of the blood passing through them. Blood flowing in the veins has lost a lot of pressure because it has passed through the narrow capillaries. The lower pressure flow means that many veins, especially those in the limbs, have valves to prevent backflow of the blood as it returns to the heart.

1. What is the function of blood vessels? ______

______

2. Why do the artery walls need to be thick with a lot of elastic tissue? ______

______

______

3. What is the role of valves in assisting the veins to return blood back to the heart? ______

______

______

4. How do the structural differences between arteries and veins relate to their functional roles? ______

______

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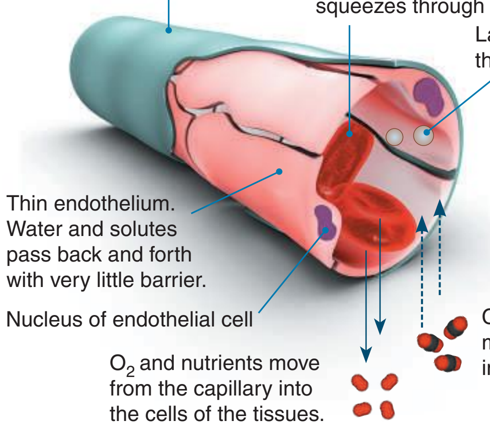
99 Capillaries and Capillary Networks

Key Idea: Capillaries are small, thin-walled vessels that allow the exchange of material between the blood and the tissues.

In vertebrates, capillaries are very small vessels that connect arterial and venous circulation and allow efficient exchange of nutrients and wastes between the blood and tissues. Capillaries form networks or beds and are abundant where metabolic rates are high. Fluid that leaks out of the capillaries has an essential role in bathing the tissues.



Exchanges in capillaries

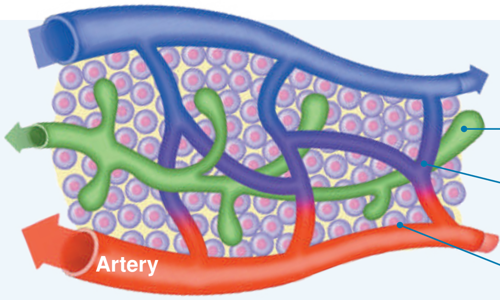
Blood passes from the arterioles into the capillaries where the exchange of materials between the body cells and the blood takes place. Capillaries have a diameter of just 5-10 µm. The only tissue present is an endothelium of squamous epithelial cells. Capillaries are so numerous that no cell is more than 25 µm from any capillary.

Blood pressure causes fluid to leak from capillaries through small gaps where the endothelial cells join. This fluid bathes the tissues, supplying nutrients and oxygen, and removing wastes (left).

The density of capillaries in a tissue is an indication of that tissue's metabolic activity. For example, cardiac muscle has a high demand for blood flow and is well supplied with capillaries. Smooth muscle is far less active than cardiac muscle and does not need such an extensive blood supply.

Blood, tissue fluid, and lymph

	Blood	Tissue fluid	Lymph
Cells	Red blood cells, white blood cells, platelets	Some white blood cells	White blood cells
Proteins	Hormones and plasma proteins	Some hormones and proteins	None
Glucose	High	None	Low
Amino acids	High	Used by body cells	Low
Oxygen	High	Used by body cells	Low
Carbon dioxide	Low	Produced by body cells	High



The fluid that leaks from the capillaries is called tissue fluid. Some of it returns to the blood at the venous end of the capillary bed, but some is drained by lymph vessels to form lymph.

- Blood transports nutrients, wastes, and respiratory gases to and from the tissues.
- Tissue fluid facilitates the transport of these between the blood and the tissues.
- Lymph drains excess tissue fluid and returns it to the general circulation. It has a role in the immune system.

1. What is the role of capillaries? ______________________

____

2. (a) Describe the structure of a capillary: ______________________

____

____

____

(b) Explain how the structure and position of capillaries (relative to the body's cells) is important in allowing the exchange of materials:

____

____

____

____

ISBN: 978-1-927309-83-4

The flow of blood through a capillary bed is called **microcirculation**. In most parts of the body, there are two types of vessels in a capillary bed: the true capillaries, where exchanges take place, and a vessel called a vascular shunt, which connects the arteriole and venule at either end of the bed. The shunt diverts blood past the true capillaries when the metabolic demands of the tissue are low. When tissue activity increases, the entire network fills with blood.

3. Describe the structure of a capillary network:

4. Explain the role of the smooth muscle sphincters and the vascular shunt in a capillary network:

5. (a) Describe a situation where the capillary bed would be in the condition labeled **A**:

(b) Describe a situation where the capillary bed would be in the condition labeled **B**:

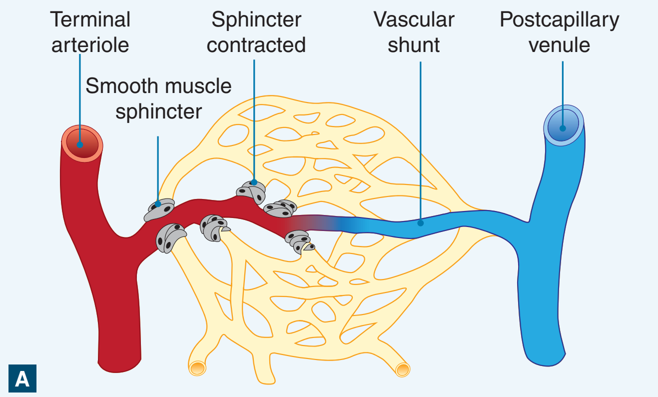
6. On the photograph right, identify:

A:

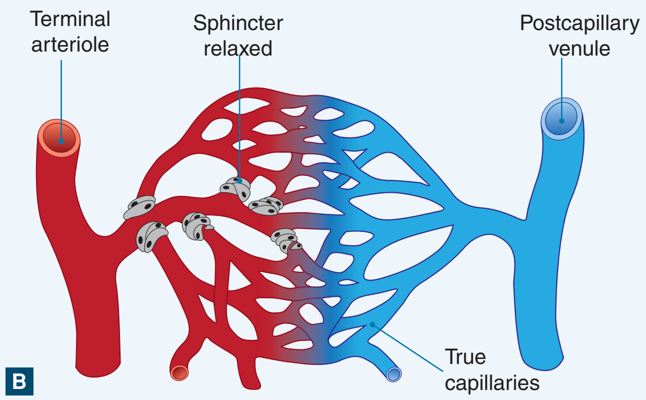
B:

C:

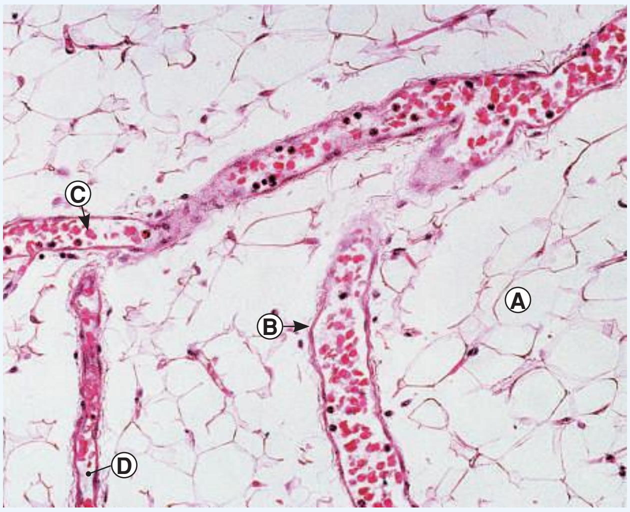
D:



When the sphincters contract (close), blood is diverted via the vascular shunt to the postcapillary venule, bypassing the exchange capillaries.



When the sphincters are relaxed (open), blood flows through the entire capillary bed allowing exchanges with the cells of the surrounding tissue.



Capillaries supply all the tissues of the body, creating extensive networks to supply cells with the nutrients and oxygen they need and remove carbon dioxide and other metabolic wastes. This capillary is moving though fat tissue.

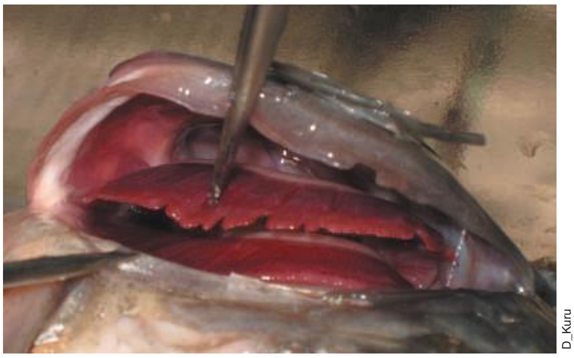
ISBN: 978-1-927309-83-4

100 KEY TERMS AND IDEAS: Did You Get It?

1. (a) On the photo of the dissection of a fish's gills, label the following: *gills, operculum, branchial arch.*

   (b) Draw arrows on the photo to show the direction of water flow when the fish was in the water.

   (c) How does the fish maximise rate of oxygen uptake in the gill?

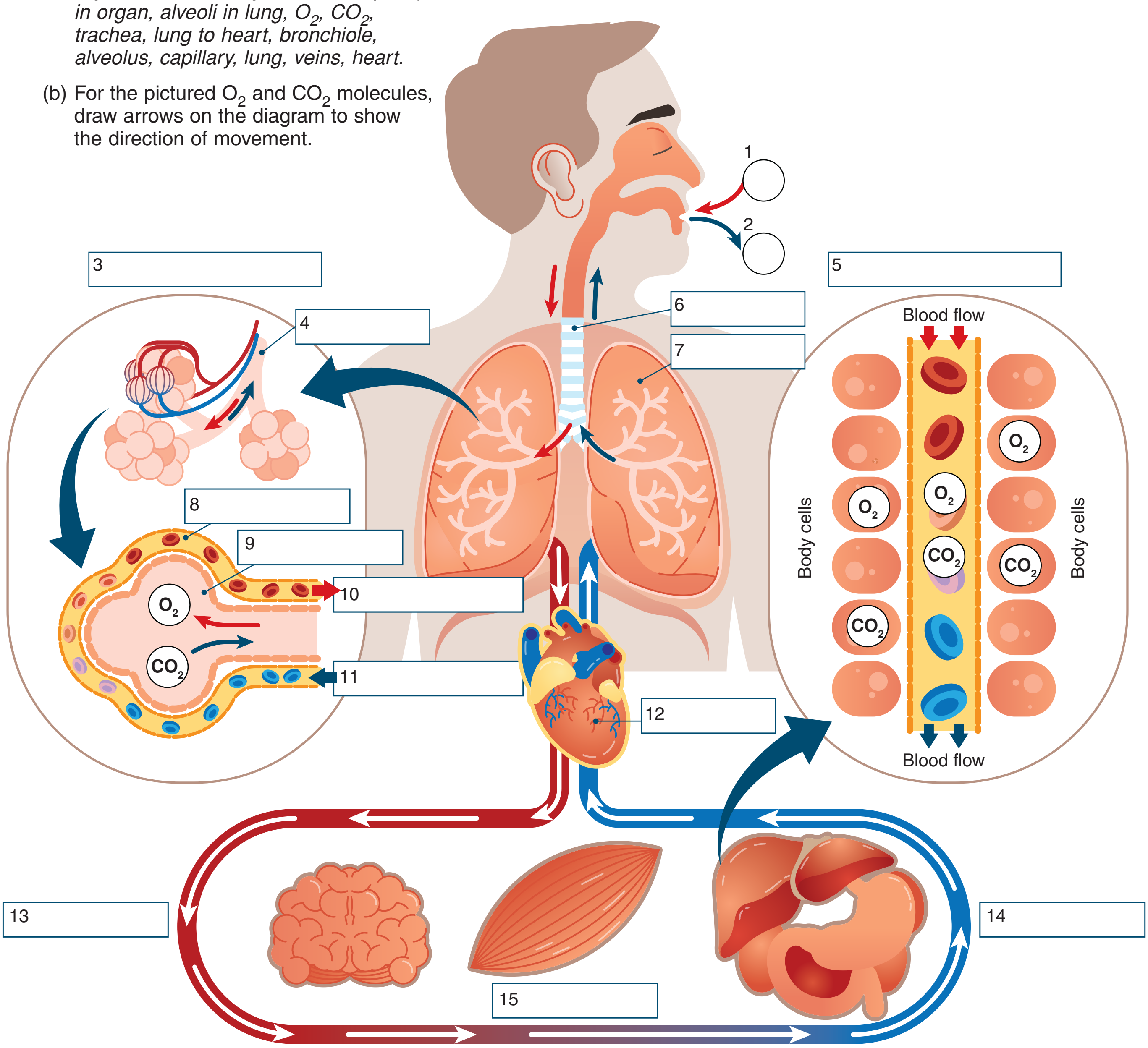


   (d) Draw a simple diagram in the box right to represent the flow of blood in the gill capillaries and the flow of water across the gill. Draw arrows to indicate the direction of oxygen movement.

2. (a) Label the diagram below (1-15) using the following word list:

   organs, heart to lung, arteries, capillary in organ, alveoli in lung, O_2, CO_2, trachea, lung to heart, bronchiole, alveolus, capillary, lung, veins, heart.

   (b) For the pictured O_2 and CO_2 molecules, draw arrows on the diagram to show the direction of movement.



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UNIT 1
Topic 2

Exchange of Nutrients and Wastes

Key terms

absorption
ammonia
amylase
Bowman's capsule
collecting duct
digestion
distal convoluted tubule
enzyme
excretion
glomerulus
intestinal villi
kidney
large intestine
lipase
Loop of Henle
microvilli
nephron
organ trafficking
organ transplant
protease
proximal convoluted tubule
small intestine
stomach
urea
uric acid
urine

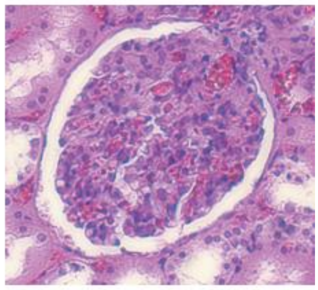
Activity number

Digestion and absorption

Key skills and knowledge

- ☐ 1 Describe the basic structure and organisation of the digestive tract in a mammal, e.g. human, including the cells and tissues making up the different regions. Distinguish regions for ingestion, digestion, absorption, and elimination. **101-104**
- ☐ 2 Identify the characteristics of the absorptive surfaces within the digestive system, e.g. the small intestine. How are these characteristics related to the structure and function of the villi? **101-104**
- ☐ 3 Describe the role of enzymes in the extracellular chemical digestion of ingested food. Describe the source, substrate, products, and optimum pH for one amylase, protease, and lipase enzyme involved in digestion. **102 103**
- ☐ 4 Describe how the different breakdown products of digestion are absorbed across the epithelium of the small intestine. Describe how the intestinal villi and the structure of the intestinal epithelial cells themselves increase the surface area for the digestion and absorption of nutrients. **103**
- ☐ 5 **PRAC** Investigate the effect of temperature on the rate of reaction of an enzyme, e.g. salivary amylase. **105**
- ☐ 6 **PRAC** Investigate the effect of pH on the rate of reaction of an enzyme, e.g. salivary amylase, catalase or lipase.





Excretion of nitrogenous wastes

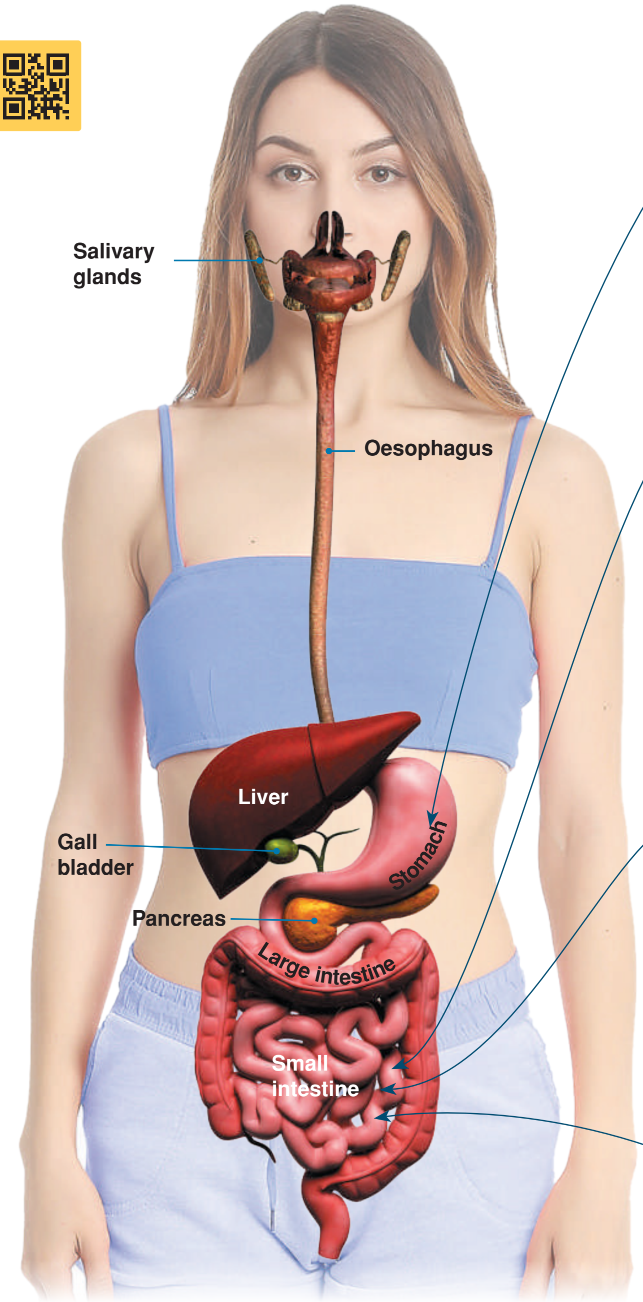
Key skills and knowledge

- ☐ 7 Recognise the different types of nitrogenous wastes produced by the breakdown of proteins. Relate the form of the nitrogenous waste excreted by different animal taxa to life history and environment. **106**
- ☐ 8 Describe the overall structure of the urinary system including kidneys, ureters, bladder, and urethra. Outline the structure and function of the mammalian kidney including the nephron and its associated capillary network. **107 108**
- ☐ 9 In more detail than above, explain the function of each of the regions of the nephron in the production of urine. Include reference to the glomerulus, Bowman's capsule, proximal convoluted tubule, loop of Henle, distal convoluted tubule, and collecting duct. **109**
- ☐ 10 Explain urine formation and excretion of wastes by glomerular filtration (ultrafiltration) and selective reabsorption and secretion across the nephron membranes. Explain how the urine is concentrated. **109**
- ☐ 11 **SHE** Discuss how the increased demand for organs for transplant has led to illegal trafficking of organs and tissue, forced donation, and transplant tourism. What ethical concerns are associated with these practices? **110**

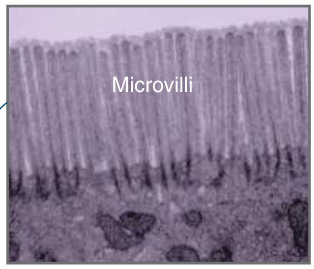
101 The Digestive System

Key Idea: The digestive tract is specialised to maximise the digestion of food, absorption of nutrients, and elimination of undigested material.

The human digestive system (gut) is a tubular tract, which is regionally specialised into a complex series of organs and glands that work in sequence to maximise the efficiency with which food is processed. Collectively, the organs of the digestive tract carry out the physical and chemical breakdown (digestion) of food, absorption of nutrients, and elimination of undigested material. The gut is a hollow, open-ended, muscular tube, and the food within it is essentially outside the body, having contact only with the cells lining the tract. External to the digestive tract are several accessory organs and glands, which add enzymes to the food to aid digestion.

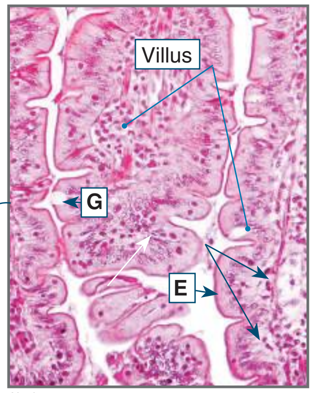


In the stomach, gastric glands contain parietal cells, which produce hydrochloric acid, and chief cells, which produce enzymes to break down protein.



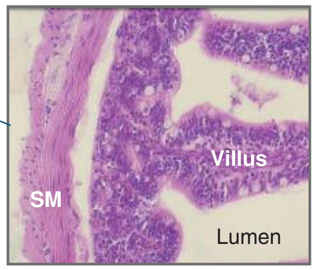
Louisa Howard, Katherine Connollly Dartmouth College

Cells lining the walls on the small intestine (the intestinal epithelium) have microscopic extensions of the plasma membrane called microvilli. These form a brush border that increases the surface area for absorption of food molecules. Under lower power microscopy, it appears as a fuzzy edge.



Nephron

In the small intestine, the intestinal epithelial cells (E) and mucus-producing goblet cells (G) make up the epithelium lining the gut wall. The wall is folded into finger like projections called villi (*sing.* villus). These further increase the surface area of the intestine.



EII

The intestinal epithelium is supported by underlying connective tissue. Two layers of smooth muscle (SM), one running lengthwise and one running around the gut, encircle the tube, contracting in waves to move food through the intestine.

1. Name three cell types of the digestive system and state their function: ______________________

____

____

2. How are villi formed? ______________________

____

3. What is the purpose of the smooth muscle surrounding the intestine? ______________________

____

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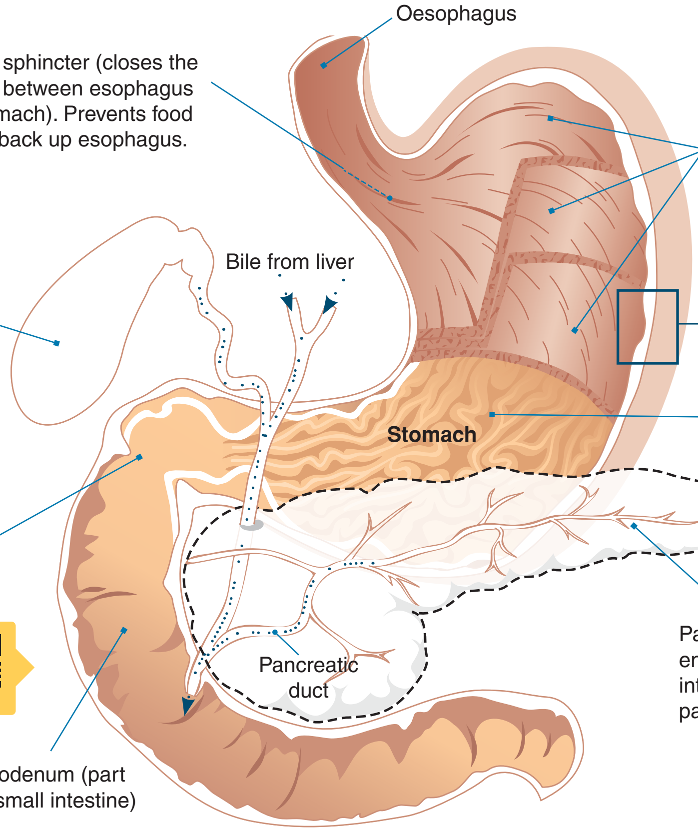
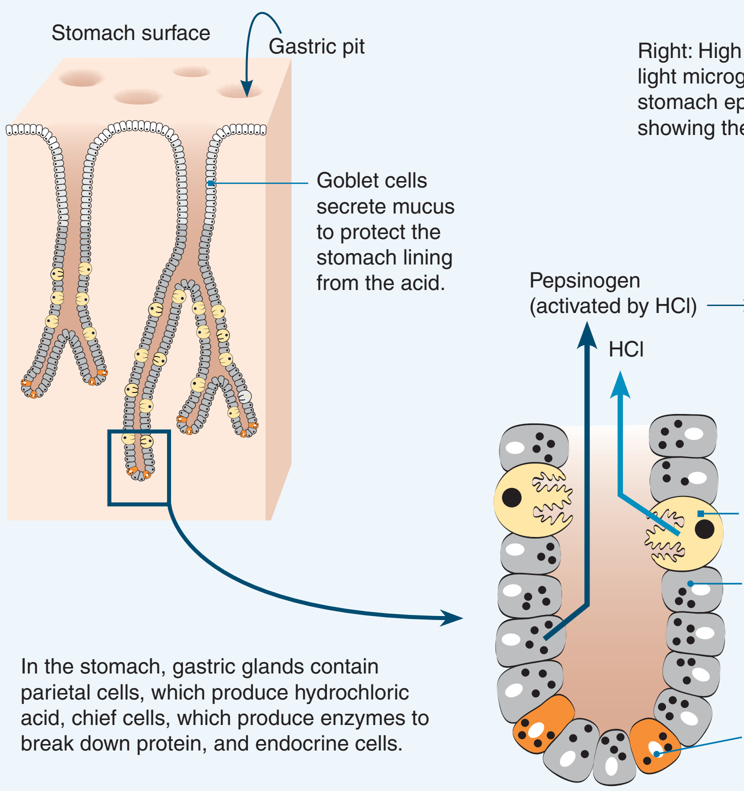
102 The Stomach and Small Intestine

Key Idea: The stomach produces acid and a protein-digesting enzyme, which break food down into a slurry, called chyme.

The **stomach** is a hollow, muscular organ between the oesophagus and small intestine. In the stomach, food is mixed in an acidic environment to produce a semi-fluid mixture called chyme. The low pH of the stomach destroys microbes, denatures proteins, and activates a protein-digesting enzyme precursor. There is very little absorption in the stomach, although small molecules (glucose, alcohol) are absorbed across the stomach wall into the surrounding blood vessels.

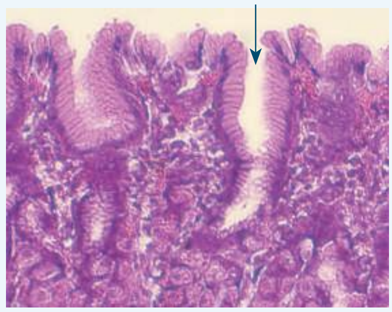


Detail of a gastric gland (stomach wall)



In the stomach, gastric glands contain parietal cells, which produce hydrochloric acid, chief cells, which produce enzymes to break down protein, and endocrine cells.

Right: High powered light micrograph of the stomach epithelium showing the gastric glands



Stomach secretions

Gastric juice
Acid (HCl) secretion
Pepsin (optimal pH 1.5-2.0) Acts on proteins and breaks them down into peptides (short chains of amino acids).

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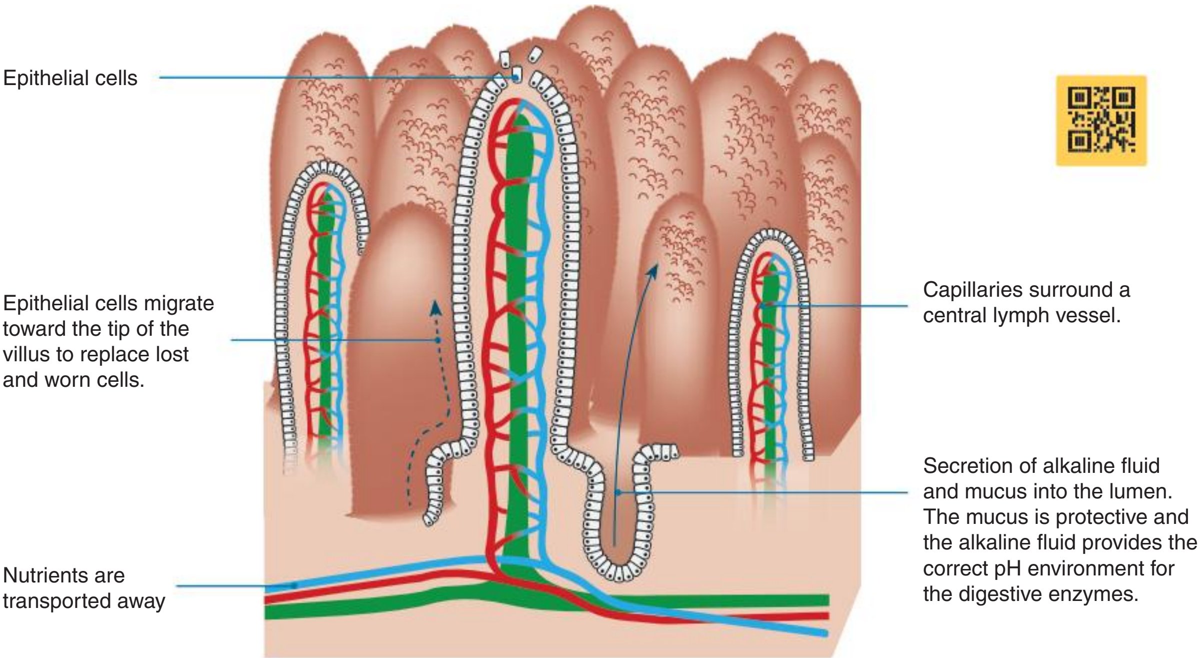
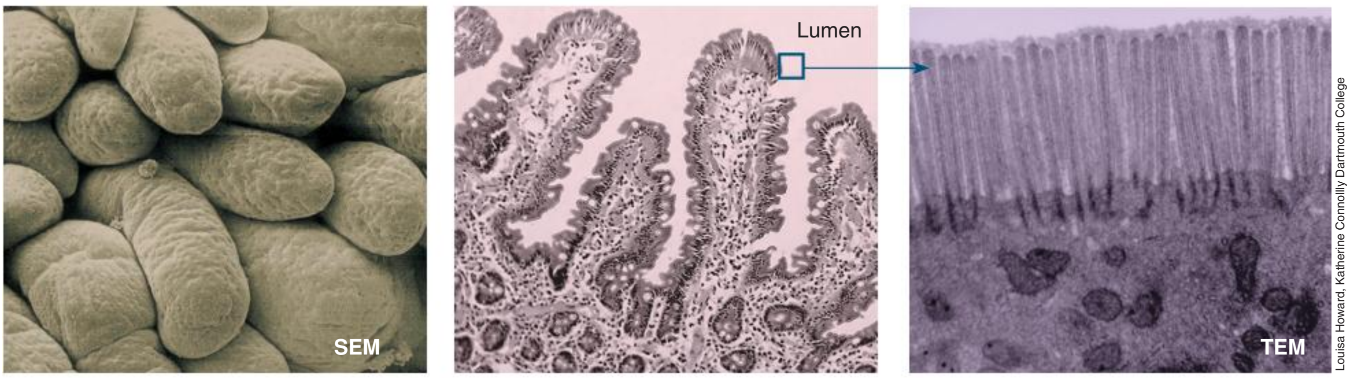
The small intestine

- The small intestine receives the chyme directly from the stomach. It is divided into three regions, which are distinguished by the cell types present: the **duodenum**, where most chemical digestion occurs, and then the **jejunum** and the **ileum**. Most absorption occurs in the jejunum and ileum.
- The intestinal lining is folded into many **intestinal villi**, which project into the gut lumen (the space enclosed by the gut). The villi increase the surface area for nutrient absorption. The **epithelial cells** that make up the lining of each villus in turn have a **brush-border** of many **microvilli**, which are primarily responsible for nutrient absorption. The membrane of the microvilli is packed with enzymes that break down food molecules for absorption.
- Enzymes bound to the microvilli of the epithelial cells, and in the pancreatic and intestinal juices, break down fats, peptides, and carbohydrates (see tables below). The small molecules produced by this digestion are then absorbed into the underlying blood and lymph vessels.
- Tubular exocrine glands and goblet cells secrete alkaline fluid and mucus into the lumen, neutralizing the acidity of the chyme entering the small intestine from the stomach and protecting the lining of the intestine from damage.



Photographs below: The intestinal villi are shown projecting into the gut lumen in a scanning electron micrograph (left image) and in a light microscope image (center image). The microvilli forming the brush border of a single intestinal epithelial cell are shown in the transmission electron micrograph (right image).



Enzymes in the small intestine break down food into small molecules that can be absorbed through the gut wall. Enzymes are present in the pancreatic juice added to the duodenum, in intestinal juice, and bound to the surfaces of the intestinal epithelial cells.

Enzymes in pancreatic juice	
Enzymes in duodenum (optimal pH)	
1. Pancreatic amylase (6.7-7.0)	1. Starch → maltose
2. Trypsin* (7.8-8.7)	2. Protein → peptides
3. Chymotrypsin* (7.8)	3. Protein → peptides
4. Pancreatic lipase (8.0)	4. Fats → fatty acids & glycerol
* secreted in an inactive form	

Enzymes in intestinal juice (IJ) and epithelium (E)	
Enzymes in small intestine (location, optimal pH)	
1. Maltase (E, 6.0-6.5)	1. Maltose → glucose
2. Peptidases (proteases) (IJ, E, ~ 8.0)	2. Polypeptides → amino acids
3. Sucrase (E, ~6.0)	3. Sucrose → fructose & glucose
4. Enteropeptidase (IJ 8.0)	4. Activates trypsin*
*Once activated, trypsin activates chymotrypsin	

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1. Summarise the structure and role of each of the following regions of the human digestive tract:

   (a) Stomach:

   (b) Small intestine:

2. (a) What is the purpose of the hydrochloric acid produced by the parietal cells of the stomach?

   (b) Explain why protein-digesting enzymes (e.g. pepsin) are secreted in an inactive form and then activated after release:

3. Identify an endocrine cell in the stomach epithelium and state its purpose:

4. How does the stomach achieve the mixing of acid and enzymes with food?

5. (a) What is the purpose of the intestinal villi?

   (b) What is the purpose of the microvilli (brush border) on intestinal epithelial cells?

6. Identify two sites for secretion of enzymes active in the small intestine. Identify an enzyme produced there and its role:

   (a) Site: Enzyme:

   Enzyme's role:

   (b) Site: Enzyme:

   Enzyme's role:

   (c) In general, do the enzymes act in acidic or alkaline conditions?

   (d) How is this pH environment generated?

7. Suggest why the small intestine is so long:

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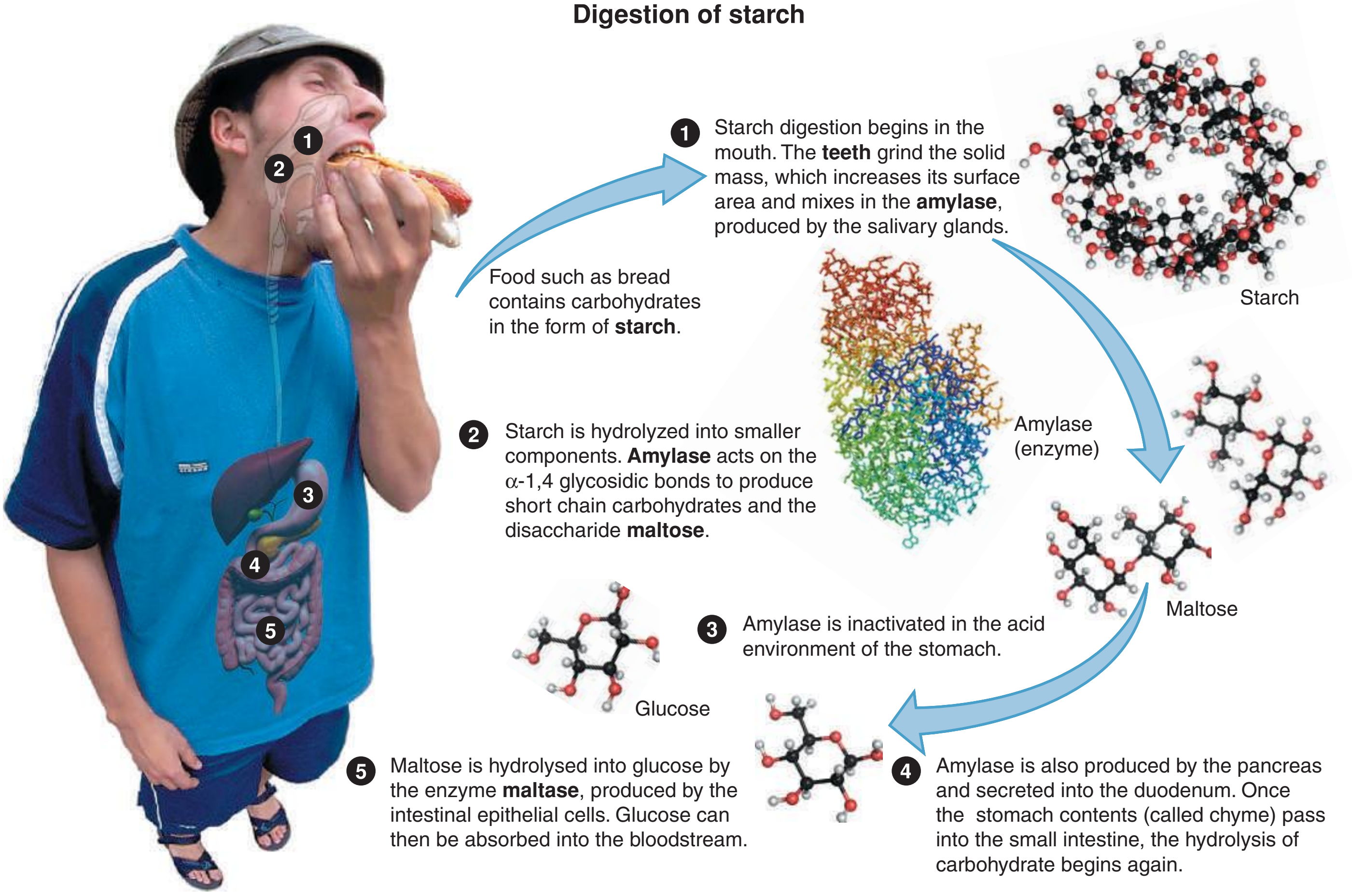
103 Digestion, Absorption, and Transport

Key Idea: Food must be digested into components small enough to be absorbed by the body's cells and assimilated. Nutrient absorption involves both active and passive transport.

Digestion breaks down food molecules into small molecules that can pass through the intestinal lining into the underlying blood and lymph vessels. For example, starch is broken down first into maltose and short chain carbohydrates such as dextrose, before being hydrolysed to the simple sugar glucose (below). Breakdown products of other foodstuffs include amino acids (from proteins), and fatty acids, glycerol, and acylglycerols (from fats). The passage of these molecules from the gut into the blood or lymph is called absorption. Nutrients are then transported directly or indirectly to the liver for storage or processing. After they have been **absorbed** nutrients can be **assimilated**, i.e incorporated into the substance of the body itself.

Digestion of starch



1. Explain the roles of amylase and maltase in starch digestion: ______________________

____

____

____

____

2. Salivary and pancreatic secretions contain amylase. Why do two digestive organs produce the same enzyme?

____

____

3. Based on the diagram opposite, predict what would happen to nutrient absorption if the villi were damaged. Explain:

____

____

____

____

28 37 64 88 89

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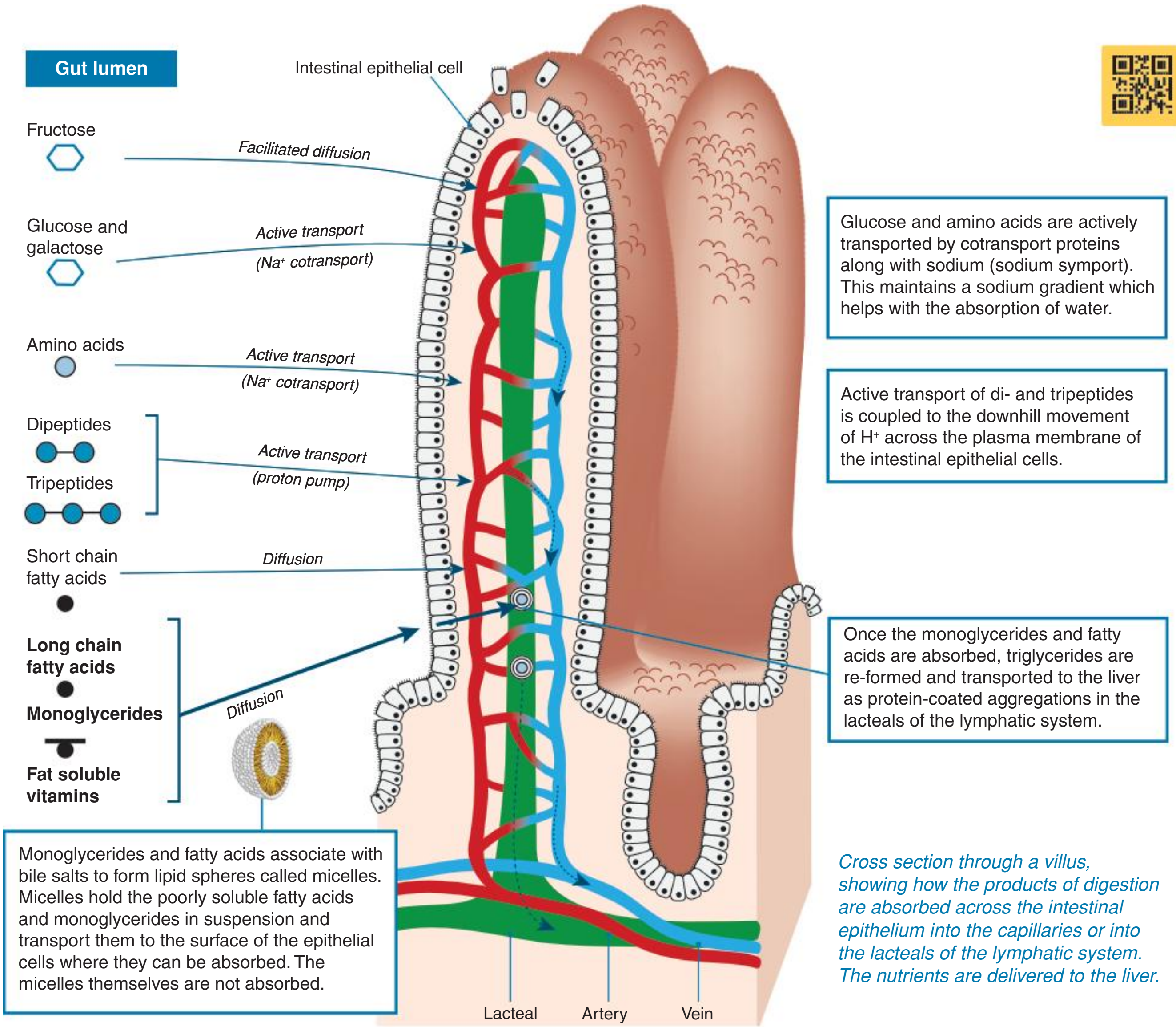
Nutrient absorption by intestinal villi



Cross section through a villus, showing how the products of digestion are absorbed across the intestinal epithelium into the capillaries or into the lacteals of the lymphatic system. The nutrients are delivered to the liver.

4. Describe how each of the following nutrients are absorbed by the intestinal villi:

   (a) Glucose: ______________________________

   (b) Fructose: ______________________________

   (c) Amino acids: ______________________________

   (d) Di- and tripeptides: ______________________________

5. Describe the two purposes of the sodium symport in the intestinal epithelium: ______________________________

6. What is the role of micelles in the absorption of lipids? ______________________________

7. How are concentration gradients maintained for the absorption of nutrients by diffusion? ______________________________

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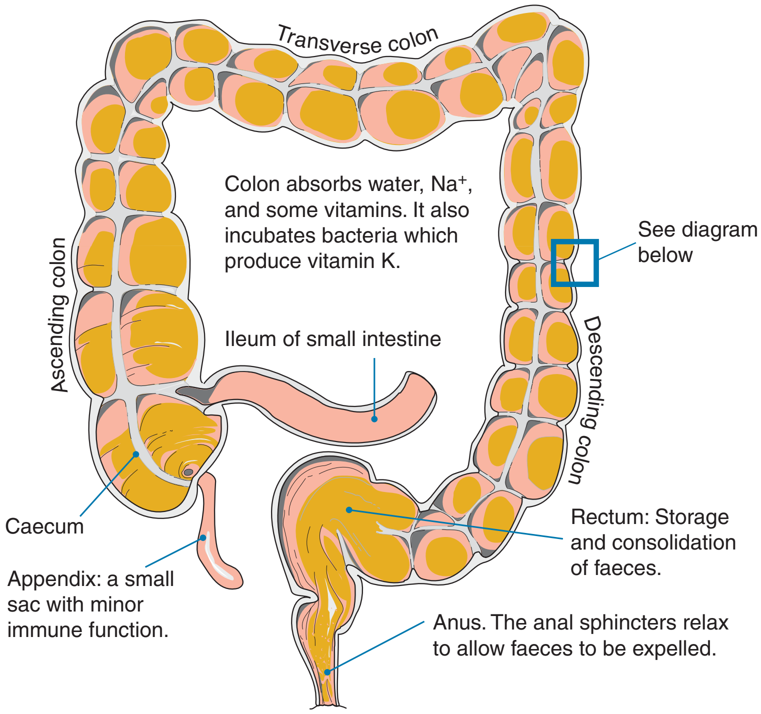
104 The Large Intestine

Key Idea: The large intestine absorbs water and solidifies the indigestible material before passing it to the rectum. Undigested waste are egested as faeces from the anus.

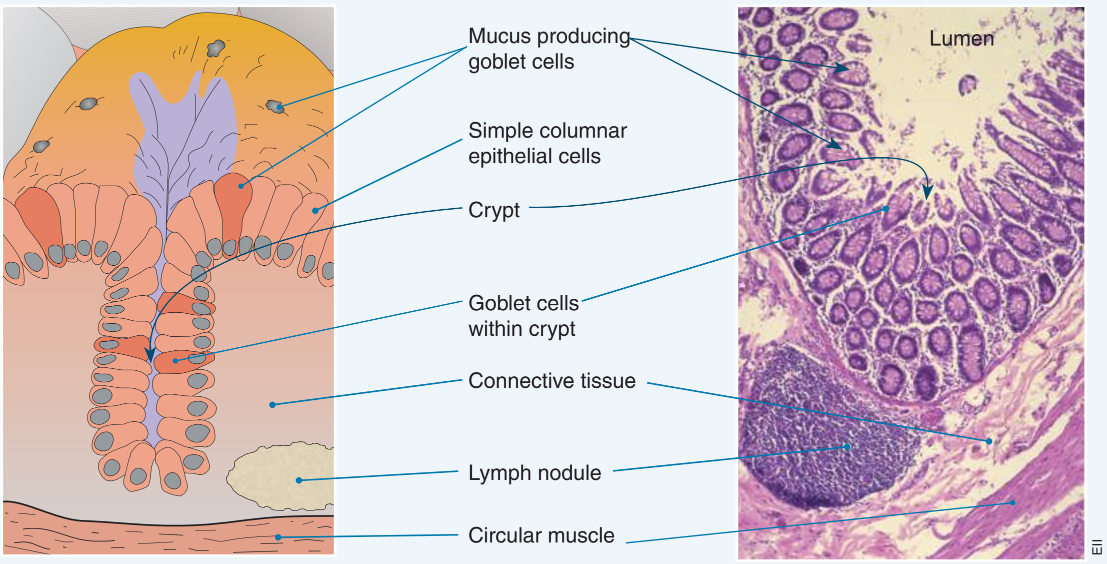
After most of the nutrients have been absorbed in the small intestine, the remaining semi-fluid contents pass into the large intestine (consisting of the appendix, caecum, colon, and rectum). The large intestine's main role is to reabsorb water and electrolytes and to consolidate the waste material into faeces, which are eliminated from the anus in a process called egestion.

- After most of the nutrients have been absorbed in the small intestine, the remaining semi-fluid contents pass into the large intestine (appendix, cecum, and colon). This mixture includes undigested or indigestible food, (such as **cellulose**), bacteria, dead cells, mucus, bile, ions, and water. In humans and other omnivores, the large intestine's main role is to reabsorb water and electrolytes and consolidate the undigested material for egestion (elimination) from the anus.
- The rectum stores the waste faecal material before it is discharged out the anus. Fullness in the rectum produces the urge to defecate. If too little water is absorbed, the faeces will be watery as in diarrhoea. If too much water is absorbed the faeces will become compacted and difficult to pass.
- Defaecation is controlled by the anal sphincters, whose usual state is to be contracted (closing the orifice). Defaecation is under nervous control.



Lining of the large intestine

The lining of the large intestine has a simple epithelium containing tubular glands (crypts) with many mucus-secreting cells. The mucus lubricates the colon wall and helps to form and move the faeces. In the photograph, some of the crypts are in XS and some are in LS.



Note the abundance of pale goblet cells.

1. What is the main purpose of the large intestine? ______________________

____

2. What are the effects of absorbing too little and too much water in the large intestine? ______________________

____

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105 Investigating Amylase Activity

Key Idea: Salivary amylase works optimally at the pH and temperature conditions of the human body. Enzyme activity outside these conditions decreases.

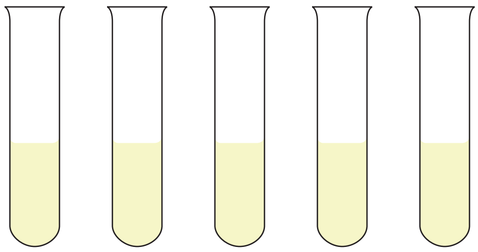
Amylase is a digestive enzyme that hydrolyses (breaks down) starch into the sugars maltose (a disaccharide) and glucose (a monosaccharide). In mammals, amylase is secreted by the salivary gland into the saliva and by the pancreas into the small intestine. Like all enzymes, amylase works best under certain conditions. In the experiments below, students looked at how pH and temperature affected amylase activity.

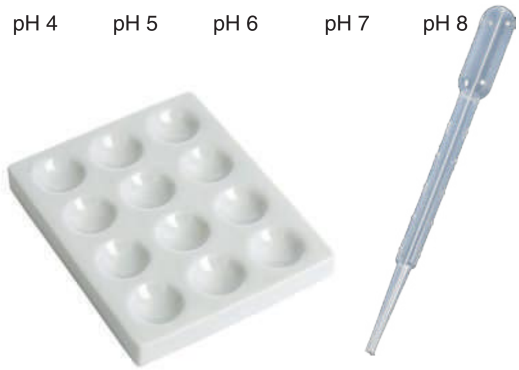
Aim
To determine the optimum pH for salivary amylase.

Hypothesis
If the normal pH for saliva is 6.5-7.5, then the optimum pH for salivary amylase should be approximately pH 7.

Background
Iodine solution (I_2/KI) is a yellow/orange colour, but in the presence of starch, it turns a blue/black colour. When the iodine solution no longer changes colour after the sample is added (i.e. remains yellow), all the starch has been hydrolysed.

Method
The experiment was performed at room temperature. A single drop of 0.1 M iodine solution was placed into the wells of spotting plates. 2 cm^3 of 1% amylase solution and 1 cm^3 of a buffered solution, pH 4, were added to the test tube. The solutions were mixed and 2 cm^3 of a 1% starch solution was added. A timer was immediately started. After 10 seconds a plastic pipette was used to remove a small amount of solution. A single drop was added to the first well of the **spotting plate** (right) and the remaining solution inside the pipette returned to the test tube. This action was repeated at 10 second intervals, adding a drop of the reaction solution into a new well until the iodine solution no longer changed colour (remained yellow/orange). The experiment was repeated using buffer solutions of pH 5, 6, 7, and 8.

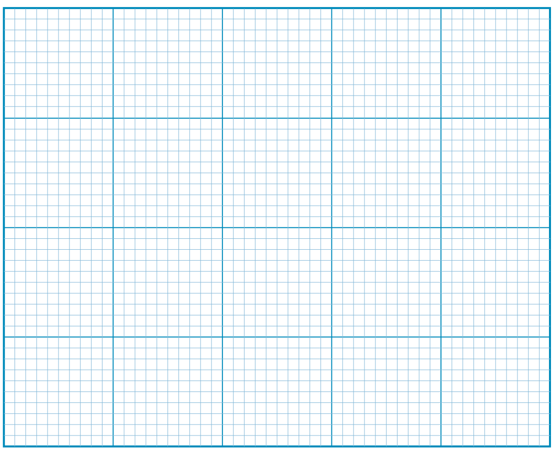




Spotting plate: each well contains a single drop of 0.1 M iodine solution (iodine dissolved in a solution of potassium iodide). Multiple spotting plates were set up to accommodate the number of tests required.

Results
The table below shows how many drops it took until there was no colour change (the iodine solution remained yellow).

pH	Number of drops until no colour change occurred	Number of seconds until no colour change occurred	Reaction rate (s^{-1})
4	19	190	
5	12	120	
6	10	100	
7	6	60	
8	29	290	



1. Why was it important to add the buffer and enzyme together before adding the starch?

2. Complete the table (left) by calculating the reaction rate for each pH (1 ÷ seconds):

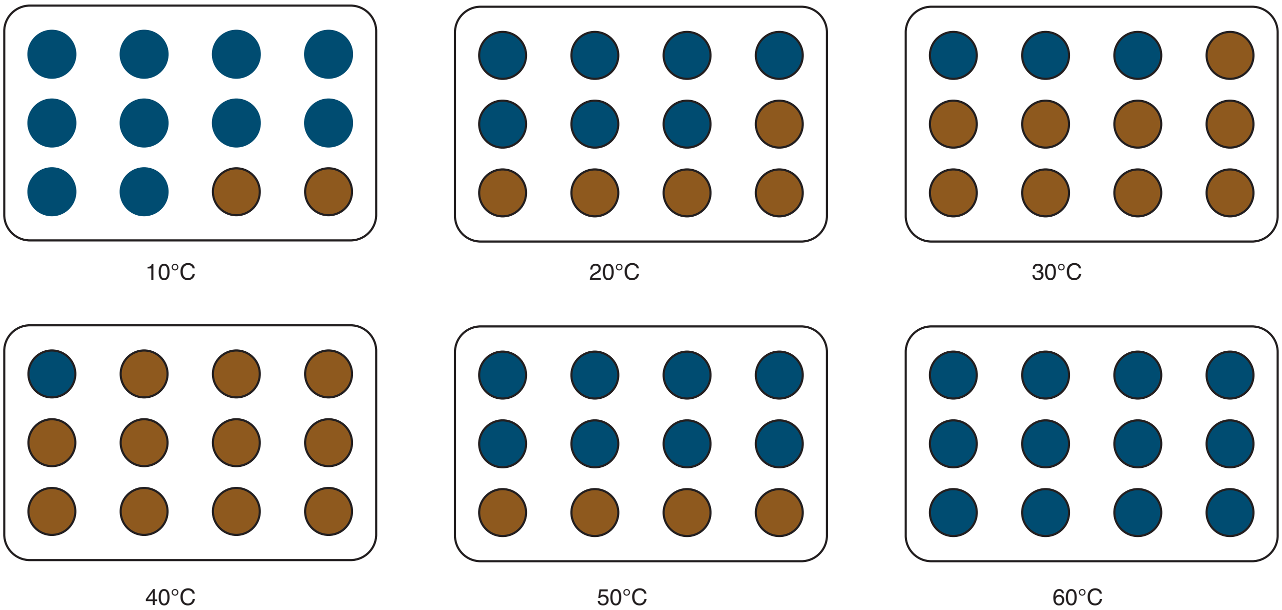
3. (a) Graph the reaction rate vs pH on the grid.

   (b) Identify the pH where amylase activity was the highest:

   (c) Is this what you had expected? Explain:

4. The students repeated the experiment at pH 1. Each sample turned blue/black when added to the iodine even after five minutes of sampling. Explain what has happened here:

In an experiment, six students wanted to determine the temperature optimum for salivary amylase. Six spotting plates were set up by adding a single drop of 0.1 M iodine solution to each well. 2 cm^3 of 1% amylase solution and 1 cm^3 of a buffered pH 7 solution was added to each of 6 test-tubes. The test tubes were placed in water baths at the test temperatures (10, 20, 30, 40, 50, and 60°C) and left for 5 minutes to equilibrate. Each student was responsible for investigating one temperature. Once the experimental temperature had been reached, 2 cm^3 of a 1% starch solution was added to the test-tube and a timer was started. After one minute, a plastic pipette was used to remove a small amount of solution. A single drop was added to the spotting plate and the colour change observed. Samples were repeated at one minute intervals until no colour change was seen. The results are shown below.



5. The students did not use any controls when they investigated the effect of pH on salivary amylase activity. What would a suitable control have been?

___

6. Why was the temperature investigation experiment carried out at pH 7? ___

___

7. Identify the temperature at which amylase shows no activity (the enzyme is denatured):

___

8. On the grid, plot the time taken for all the starch to be digested against temperature (do not plot 60°C):

9. Identify the optimum temperature for amylase:

___

10. Describe how temperature affects the activity of amylase:

___

___

___

___

11. Predict amylase activity below 10°C and give a reason for your prediction:

___

___

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ISBN: 978-1-927309-83-4

106 Nitrogenous Wastes in Animals

Key Idea: Nitrogenous wastes are produced from the breakdown of nitrogen containing compounds. They must be excreted before they accumulate to toxic levels.

The process of removing the waste products of cellular metabolism is called excretion. These waste products include toxic nitrogenous wastes from the metabolism of amino acids and nucleic acids, as well as water, CO_2, and excess ions. The simplest breakdown product of nitrogen-containing compounds is ammonia, a highly toxic molecule that cannot be retained in the body for long. Most aquatic animals excrete ammonia immediately into the water where it is washed away. Other animals convert the ammonia to a less toxic form (urea or uric acid) that can remain in the body for a short time before being excreted. The form of the excretory product in terrestrial animals depends on the type of organism and its life history. Terrestrial animals that lay eggs produce uric acid rather than urea, because it is non-toxic and very insoluble. It remains as an inert solid mass in the egg until hatching.

Breakdown of nitrogen containing compounds (amino acids and nucleic acids)

Nitrogen released as ammonia

Ammonia (NH_3)
A small, highly toxic molecule

Excreted directly without conversion

Converted to:

Converted to:

Ammonia (NH_3)	**Urea ($CO(NH_2)_2$)**	**Uric acid ($C_5H_4N_4O_3$)**
Excreted directly into the water where it is diluted	**Produced in the liver via the urea cycle**	**Made from NH_3 at high energy cost**

Excreted directly with no energy cost by aquatic invertebrates and most fish. Ammonia is highly toxic and these animals quickly dilute it in the water.

Excreted by all mammals, some fish, and most amphibians. Urea is 100,000 times less toxic than ammonia and is soluble so it can be excreted in a concentrated form.

Excreted as a white paste by birds, insects, land snails, and some reptiles. Uric acid has a very low solubility and is virtually non-toxic.

Increasing amounts of energy needed to produce the end product.
Decreasing toxicity and less water needed for excretion.

1. What is the main source of nitrogen-containing wastes in animals? ______________________

____

2. (a) Describe one advantage of uric acid as an excretory product (relative to urea and ammonia): ______________________

____

(b) Describe one disadvantage of ammonia as an excretory product: ______________________

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3. Discuss the relationship between the type of excretory product and an animal's environment: ______________________

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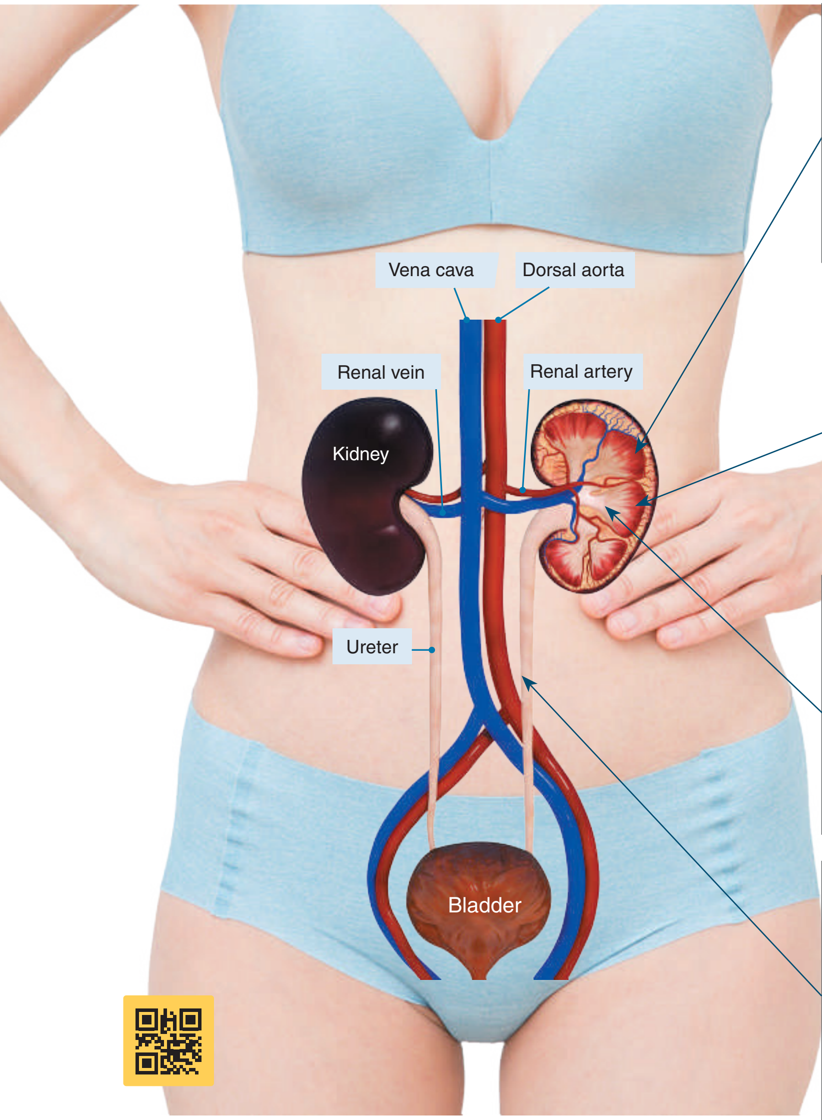
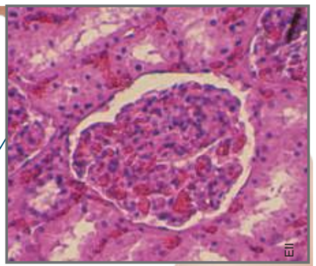
ISBN: 978-1-927309-83-4

107 The Excretory System

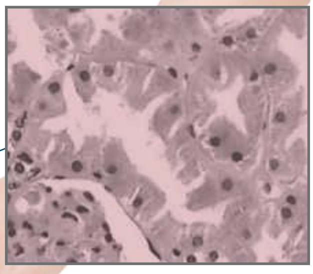
Key Idea: The excretory system is responsible for removing metabolic wastes from the body by filtering the blood.

The mammalian urinary system consists of the kidneys and bladder, and their associated blood vessels and ducts. The kidneys have a plentiful blood supply from the renal artery. The blood plasma is filtered by the kidneys to form urine. Urine is produced continuously, passing along the ureters to the bladder. Mammalian kidneys are very efficient, producing a urine that is concentrated to varying degrees depending on fluid requirements at the time.

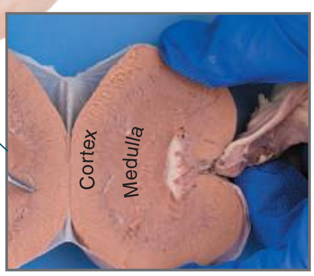




Blood is filtered in the kidneys by the **glomerulus**, a dense knot of capillaries. Blood is forced through them at high pressure, a process known as ultrafiltration. The filtrate is collected in the **Bowman's capsule** which surrounds the glomerulus.



The filtrate moves from Bowman's capsule to the convoluted tubules. These are lined with cuboidal epithelial cells, which have a brush border of microvilli to enhance absorption of substances from the filtrate. The glomerulus, capsule, and tubules form the functional unit structure of the kidney, the nephron.



The thousands of filtering elements of the kidney (the nephrons) are aligned and organised in a particular way in the kidney. The glomeruli and convoluted tubules are found in the outer region or cortex, while the "loop of Henle" is found in the inner region of medulla.

The filtrate passes to the renal ducts and then to the **ureter** and finally to the bladder. The kidney itself is bean shaped and is around 10 cm long in humans.

1. What is the purpose of the microvilli in the epithelial cells of the convoluted tubules? ______________________

____

2. (a) How is filtrate formed? ______________________

____

____

(b) How is the filtrate modified? ______________________

____

3. The circulation rate of blood through the renal artery is about 1.2 L min^{-1}, about one quarter of the heart's total output. Why does so much blood need to pass through the kidneys every minute?

____

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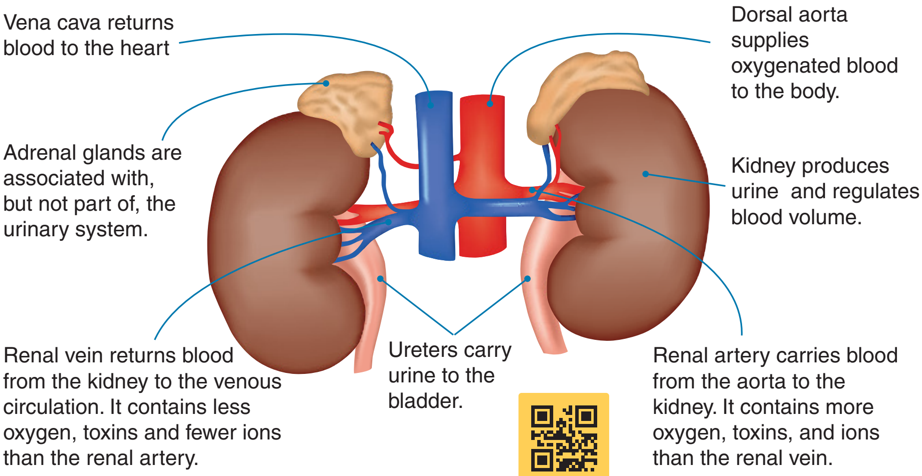
108 Kidney Structure

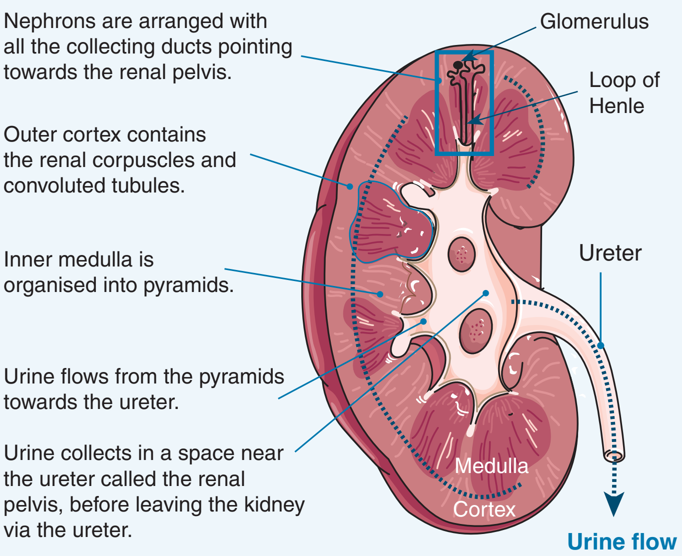
Key Idea: In terrestrial vertebrates, the kidneys excrete nitrogenous waste and maintain water and solute balance.

The central organs of the excretory system in humans and other mammals are the kidneys. They act as a selective filter of the blood, removing metabolic wastes while retaining useful substances, such as valuable ions and glucose. The kidneys receive blood under high pressure via the arterioles from the renal artery. This high pressure forces blood plasma out of the capillaries, forming a fluid called filtrate, which is then modified as it passes through the kidney to form the urine. Each day the kidneys filter about 180 L of plasma. Most of this is reabsorbed, leaving a daily urine output of about 1 L. By adjusting the composition of the fluid excreted, the kidneys help to maintain the body's internal chemical balance.

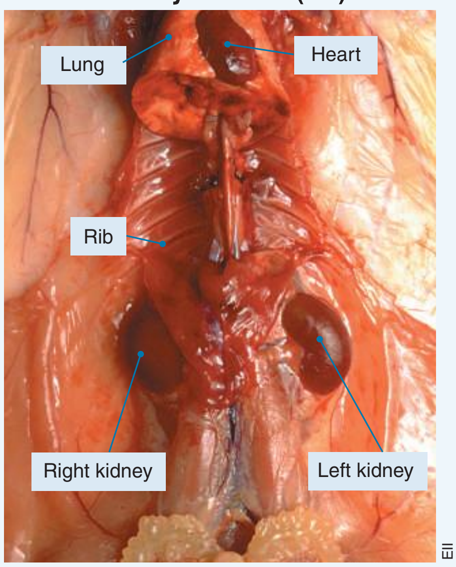
- The kidneys are bean shaped organs that lie at the back of the abdominal cavity to either side of the spine (below right).
- Human kidneys (right) are ~100-120 mm long and 25 mm thick. The precise alignment of the nephrons (the filtering elements of the kidney) and their associated blood vessels gives the kidney tissue a striped appearance (below). Each kidney contains more than 1 million nephrons. Nephrons are selective filter elements, which regulate blood composition and pH, and excrete wastes and toxins.



Kidney internal structure



Kidneys *in-situ* (rat)



1. What is the function of the kidney? ______

2. Calculate the percentage of the plasma reabsorbed by the kidneys: ______

3. The kidney's are located near the lower part of the ribcage. What do you think is the significance of this location?

4. Describe the location and orientation of the nephrons in a kidney: ______

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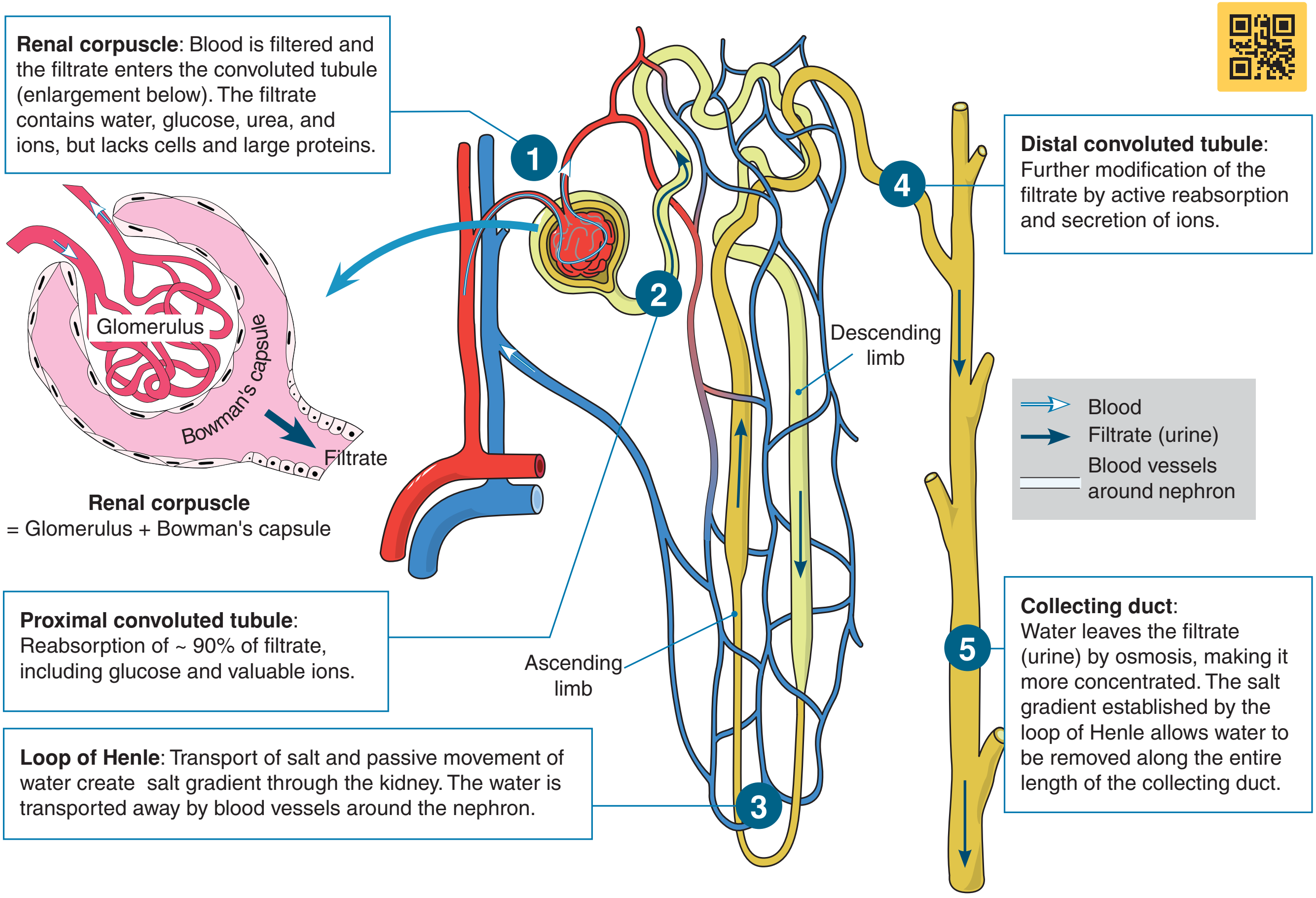
109 Nephron Structure and Function

Key Idea: The functional unit of the kidney is the nephron. It is a selective filter element, comprising a renal corpuscle and its associated tubules and ducts.

Ultrafiltration, i.e. forcing fluid and dissolved substances through a membrane by pressure, occurs in the first part of the nephron, across the membranes of the capillaries and the glomerular capsule. The formation of the glomerular filtrate depends on the pressure of the blood entering the nephron (below). If it increases, filtration rate increases; when it falls, glomerular filtration rate also falls. This process is precisely regulated so that glomerular filtration rate per day stays constant. The initial filtrate, now called urine is modified through secretion and tubular reabsorption according to body's needs at the time.



1. What is the purpose of the nephron? ______________________________

____

____

2. Summarise the main activities in each of the five regions of the nephron:

(a) Renal corpuscle: ______________________________

(b) Proximal (near) convoluted tubule: ______________________________

(c) Loop of Henle: ______________________________

(d) Distal (far) convoluted tubule: ______________________________

(e) Collecting duct: ______________________________

3. A kidney contains 1.5 million nephrons (filtering units). A person only needs 300,000 working nephrons to survive.

(a) What percentage of nephrons actually need to be working for a person to survive? ______________________________

(b) Why is this important to someone with a damaged kidney? ______________________________

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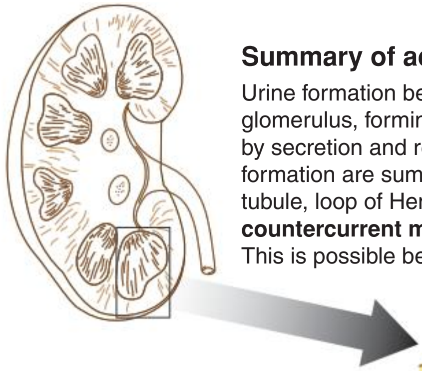


Summary of activities in the kidney nephron

Urine formation begins by ultrafiltration of the blood, as fluid is forced through the capillaries of the glomerulus, forming a filtrate similar to blood but lacking cells and proteins. The filtrate is then modified by secretion and reabsorption to add or remove substances (e.g. ions). The processes involved in urine formation are summarized below for each region of the nephron (glomerulus, proximal convoluted tubule, loop of Henle, and distal convoluted tubule), and the collecting duct. The loop of Henle acts as a **countercurrent multiplier**, establishing and increasing the salt gradient through the medullary region. This is possible because the descending loop is freely permeable to water but the ascending loop is not.

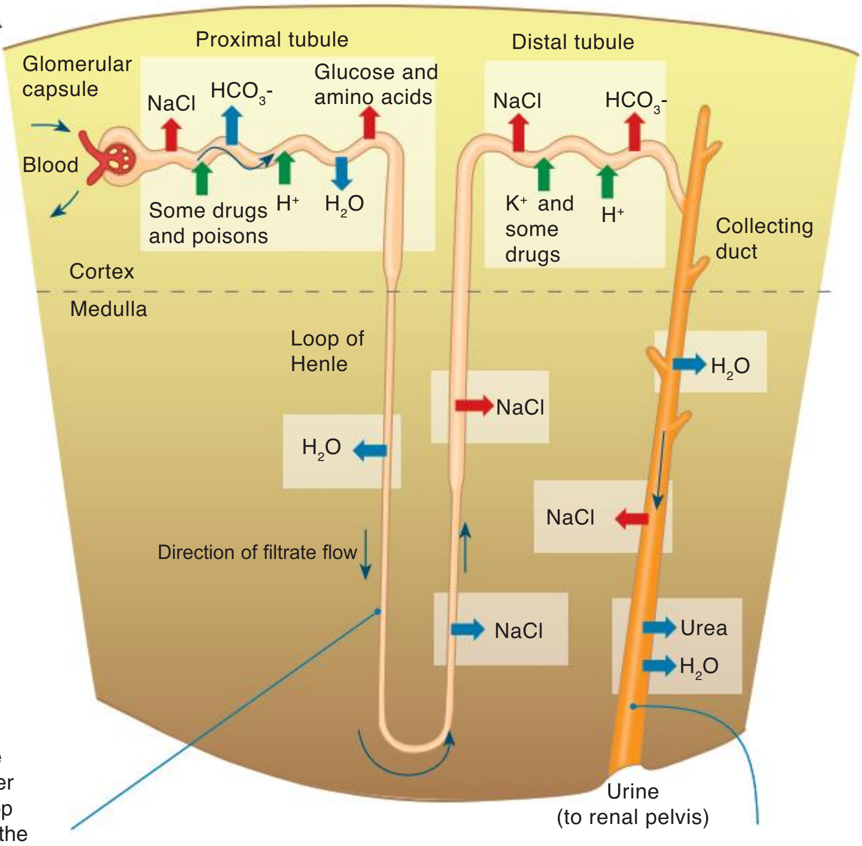
Filtrate

- H_2O
- Salts (NaCl, etc.)
- HCO_3^- (bicarbonate)
- H^+
- Urea
- Glucose; amino acids
- Some drugs

Reabsorption

- Active transport
- Passive transport

Secretion
(active transport)



The thick ascending limb of the loop of Henle pumps out sodium and chloride ions from the filtrate. This produces a high solute concentrate in the interstitial space. This in turns draws water by osmosis from the descending limb of the loop Henle into the interstitial space. The water and the ions are transported away by the capillaries. The countercurrent flow within the descending and ascending limbs multiplies the osmotic gradient between the tubular fluid and the interstitial space.

Reabsorption of a small amount of urea from the urine helps to maintain the osmotic gradient for the removal of water.

4. (a) What is the purpose of the salt gradient in the kidney? ______________________

(b) How is this salt gradient produced? ______________________

5. (a) The kidneys of desert mammals are adapted to conserve water. One of these adaptations is in the length of the loop of Henle. Would a desert mammal have a longer or shorter loop of Henle that a non-desert adapted mammal?

____

(b) Explain why: ______________________

6. Where in the nephron is water reabsorbed? ______________________

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110 Organ and Tissue Transplantation

Key Idea: There are many more people needing organ and tissue transplants that there are donors. And not all organs are obtained ethically...

Need a new kidney? It'll cost you just US$62,000. What about a heart? That's just US$160,000. If you've got the right broker and surgeon who'll look the other way. Illegal organ trafficking is worth big money throughout the world. Those stories about going out for the night and waking up in a bath of ice minus a kidney aren't entirely true, but they're also not entirely false. As with all good stories, there is a little bit of truth to them.

Organ trafficking is the (illegal) sale and purchase of human organs for transplantation. The most commonly trafficked organ is the kidney. Donors can live perfectly well with just one kidney, so they can be bought or sold more easily, especially from the poor or desperate.

There are tens of thousands of people throughout the world needing organ transplants. In many countries, these organs are obtained from donors, usually after their death. Waiting lists are based on need, tissue matches, and other medical information. However, there are many more people waiting for transplants than there are organ donors. Some people are prepared to pay large sums of money for an organ transplant, either to move them up the waiting list or avoid the usual processes and obtain preferential treatment through a private clinic.

- Guidelines on organs donation set up by the WHO include that organ donation should be altruistic (for no commercial gain). In 2013, Australia legalised financial compensation for organ donors. This is limited and aimed at compensating the donor for taking time off work while recovering.
- Some people argue that organs should be able to be bought and sold legally. This would allow low-income people to benefit financially and lets people needing a transplant to quickly get on with their lives. However most medical professions reject this on the basis of ethical issues, which include the exploitation of the poor or desperate and the treatment of human organs as commodities to be bought and sold.
- Transplant tourism is the overseas travel of people to places where they can acquire a needed organ. It refers mainly to the buying and selling of organs as a purely commercial venture.
- The WHO have identified a number of websites offering organ transplants as tourism packages including Liver4you.org.
- Obtaining organs from paid (often exploited) donors raises the risk of spread of disease, including hepatitis and HIV. There can also be a lack of follow up care, including anti-rejection drugs, so the transplant may fail. Studies have shown there are a higher number of failed operations from illegal organ transplants than from legal surgeries.

- Transplantation of a healthy kidney from a donor is the preferred treatment for end-stage kidney failure. The organ is usually taken from a person who has just died, although kidneys can also be taken from living donors. The damaged kidneys are left in place and the new kidney transplanted into the lower abdomen (right). If recipients comply with medical requirements (e.g. correct diet and medication) over 85% of kidney transplants are successful.
- The two major problems associated with kidney transplants are lack of donors and tissue rejection. Cells from donor tissue have different antigens to those of the recipient, and the recipient's immune system will attack the new kidney, recognising it as foreign.
- Tissue-typing and the use of immunosuppressant drugs helps to decrease organ rejection rates. In the future, the transplant of genetically modified organs from other species may help to solve the problems of supply and immune rejection.

1. In Australia, there are more than 1000 people waiting for a kidney transplant but fewer than 250 live donors. As a group, discuss the issues surrounding organ transplants, including the lack of willing donors and how this might be solved. Is financial compensation ethical? How far should compensation go? Should people be able to sell their own organs? Summarise your discussion below:

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111 KEY TERMS AND IDEAS: Did You Get it?

1. Match each term to its definition, as identified by its preceding letter code.

amylase ....

excretion ....

glomerulus ....

kidney ....

loop of Henle ....

small intestine ....

urea ....

A Part of the gut that receives chyme directly from the stomach. Here, digestive enzymes are added, which break down food and food molecules reabsorbed into the blood.

B Part of the kidney nephron between the proximal and distal convoluted tubules. Its function is to create a salt gradient through the medullary region of the kidney.

C The primary nitrogenous excretory product of mammals.

D Enzyme produced by the salivary glands and pancreas that breaks down starch into smaller maltose molecules.

E Elimination of the waste products of metabolism.

F Bean shaped excretory organ in vertebrates, which removes and concentrates metabolic wastes from the blood.

G The collection of capillaries within Bowman's capsule in the kidney where ultrafiltration of the blood plasma occurs.

2. (a) What structures from the small intestine of a mammal are shown in the photograph (right)?

____

(b) What is their function? ______________________________

____

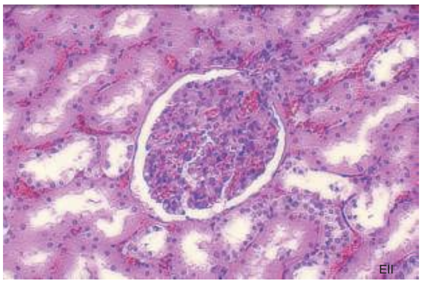
____

3. (a) Name the excretory organ of vertebrates: ______________________________

(b) Name the selective filtering element of the kidney: ______________________________

(c) The length of this structure is directly related to the ability of an organism to concentrate urine: ____________

4. In the micrograph below label the following: glomerulus, capsular space, convoluted tubules, Bowman's capsule.



5. The drawing right depicts nephrons from the kidney.

(a) How many nephrons are shown? ____________

(b) Label the diagram to show glomerulus, Bowman's capsule, proximal convoluted tubule, distal convoluted tubule, loop of Henle, collecting duct.

(c) Draw arrows to indicate the direction of urine flow.

(d) In a different colour, label where the reabsorption of glucose would occur.

(e) What significant feature is missing from this diagram?

____

____

____

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UNIT 1
Topic 2

Plant Systems: Gas Exchange and Transport

Key terms

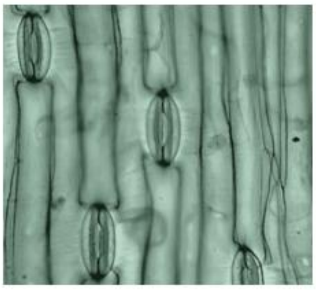
cohesion-tension hypothesis
companion cell
cuticle
epidermis
guard cells
leaf
mesophyll
phloem
sieve plate
sieve tube
stem
stomata
translocation
transpiration
transpiration stream
vascular tissue
xylem

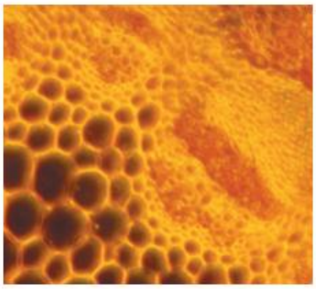
Activity number

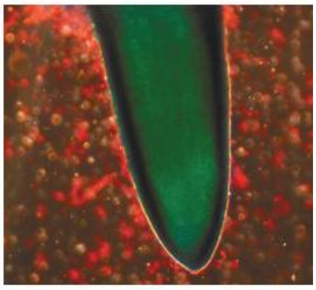
Gas exchange in plants

Key skills and knowledge

- ☐ 1 Recall the hierarchy of organisation in a vascular plant, with reference to how its cells are specialised into tissues and tissues into organs for the purposes of gas exchange, photosynthesis, and nutrient and water uptake and transport. **112**
- ☐ 2 Describe the role of stomata and guard cells in controlling the movement of gases (oxygen, carbon dioxide, and water vapour) in plants. **113**
- ☐ 3 Describe the structure of a leaf in a generalised plant and explain how it facilitates the exchange of gases between the environment and the plant tissues. **113**
- ☐ 4 *SKILL* Remove the epidermis of a leaf, cut sections, and prepare wet mounts to view with a microscope. **55-57**
- ☐ 5 *PRAC* Make wet mounts (or view prepared slides) of the leaf epidermis to identify, draw and label stomata, guard cells, and epidermal cells. **55-57 60**
- ☐ 6 *PRAC* Investigate differences in the number of stomata in the upper and lower epidermis of the leaf and between different species. **162**
- ☐ 7 Explain the relationship between photosynthesis and the main tissues of the leaves (spongy and palisade mesophyll, epidermis, cuticle, and vascular bundles). **113**
- ☐ 8 *PRAC* Investigate the conditions necessary for photosynthesis by comparing the starch present in normal, variegated, and destarched leaves. **114**







Vascular tissue and plant transport

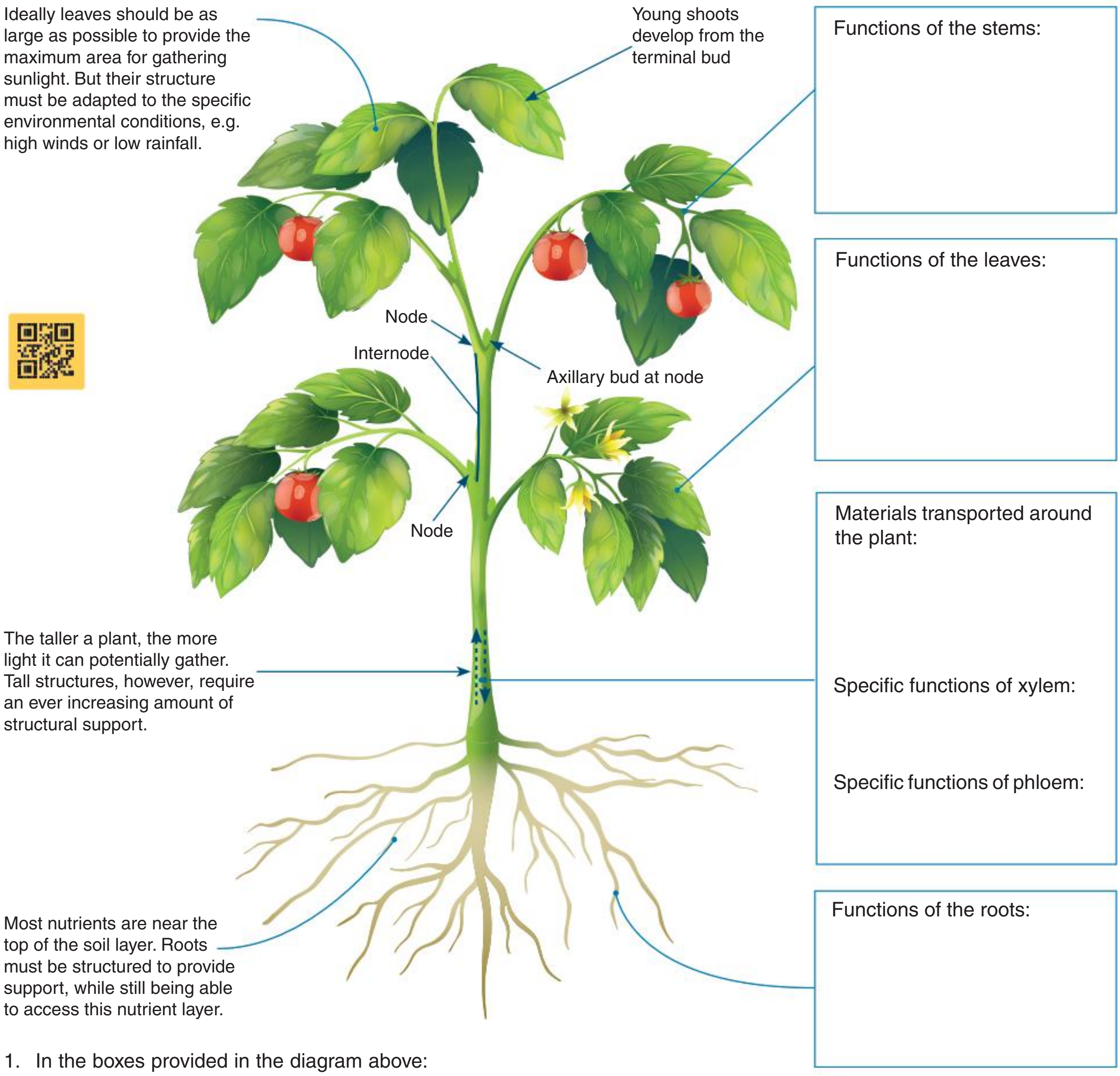
Key skills and knowledge

- ☐ 9 Describe and contrast the structure of xylem and phloem tissue. Include reference to vessels and tracheids in xylem and sieve tubes, sieve plates, and companion cells in phloem. **115 116**
- ☐ 10 Explain the movement of water and dissolved minerals through the xylem (the transpiration stream). Include reference to transpiration pull, the cohesion-tension hypothesis, and root pressure. **117 118**
- ☐ 11 Identify the factors affecting the rate of transpiration and describe and explain their effects. Include reference to light, temperature, wind, and humidity. **119**
- ☐ 12 *PRAC* Use a potometer to estimate transpiration rates in different plants or under different conditions. Interpret data from investigations of transpiration. **120**
- ☐ 13 Explain the source to sink transport of the sugars and some minerals via translocation in the phloem.

112 The Plant Body

Key Idea: The plant body consists of connected shoot and root systems. The shoot system collects carbon dioxide, oxygen, and light and produces sugars. The root system collects water and nutrients from the soil.

As terrestrial organisms, plants have two interdependent systems to take advantage of and to solve the problems of living on land. The **shoot system**, consisting of **stems**, **leaves** and **reproductive structures**, has evolved to collect carbon dioxide, oxygen and light, and to disperse pollen and seeds. The **root system** has evolved to collect water and nutrients from the soil and to provide anchorage to the ground or substrate. These systems are integrated to form the closely linked support and transport systems. If a plant is to grow to any size, it must have ways to hold itself up against gravity and to move materials around its body. Vascular tissues (xylem and phloem) link all plant parts. Water and minerals are transported in the xylem, while manufactured food is transported in the phloem. All plants rely on fluid pressure within their cells (turgor) to give some support to their less rigid structures e.g. leaves and flowers.



1. In the boxes provided in the diagram above:
   (a) Describe the main functions of the leaves, roots and stems (remember that the leaves themselves have leaf veins).
   (b) List the materials that are transported around the plant body.
   (c) Describe the functions of the transport tissues: xylem and phloem.

2. Name the solvent for all the materials that are transported around the plant: ______________________

3. What factors are involved in determining how tall a plant could potentially grow? ______________________

____

____

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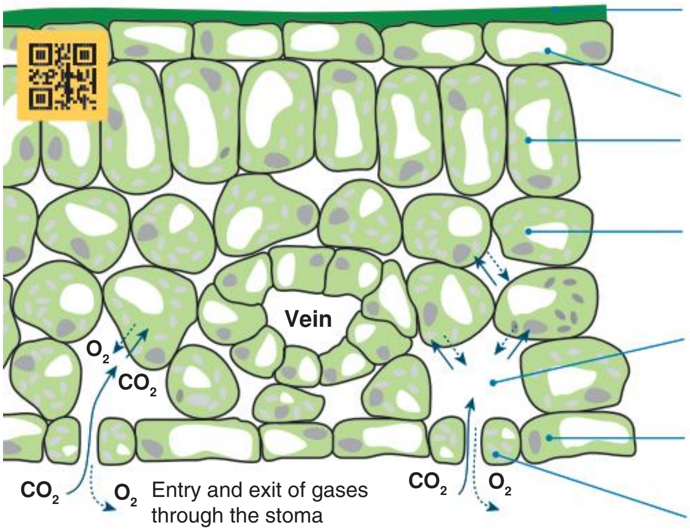
113 Gas Exchange and Stomata

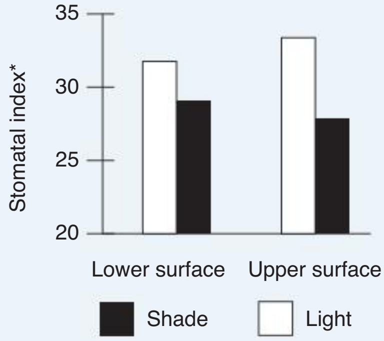
Key Idea: Gas exchange through stomata is associated with water losses. Guard cells help regulate these water losses.

The leaf epidermis of angiosperms is covered with tiny pores, called **stomata**. Angiosperms have many air spaces between the cells of the stems, leaves, and roots. These air spaces are continuous and gases are able to move freely through them and into the plant's cells via the stomata. Each stoma is bounded by two **guard cells**, which together regulate the entry and exit of gases (including water vapour). Although stomata permit gas exchange between the air and the photosynthetic cells inside the leaf, they are also the major routes for water loss through transpiration.

Gas exchanges and the function of stomata



Net gas exchanges in a photosynthesising dicot leaf



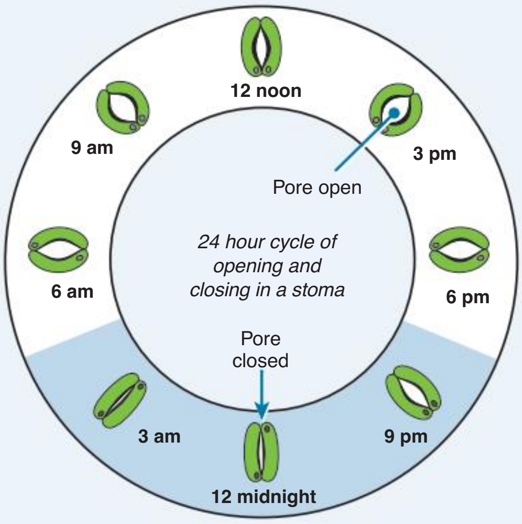
*Stomatal index is the percentage number of stomata compared to all the epidermal cells in a unit area of leaf.

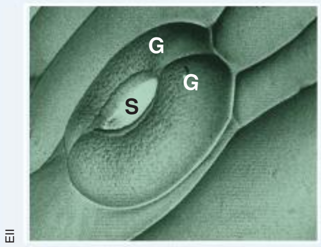
An increase in light intensity on mature leaves increases the number of stomata developing on young leaves.

- Gases enter and leave the leaf through stomata. Inside the leaf (as illustrated for a dicot, above), the large air spaces and loose arrangement of the spongy mesophyll facilitate the diffusion of gases and provide a large surface area for gas exchanges.
- Respiring plant cells use oxygen (O_2) and produce carbon dioxide (CO_2). These gases move in and out of the plant and through the air spaces by diffusion.
- When the plant is photosynthesising, the situation is more complex. Overall there is net consumption of CO_2 and net production of oxygen. Fixation of CO_2 maintains a gradient in CO_2 concentration between the atmosphere (high) and the leaf tissue (low).
- Oxygen is produced in excess of respiratory needs and diffuses out of the leaf. These **net** exchanges are indicated by the arrows on the diagram.

The cycle of opening and closing of stomata

The opening and closing of stomata shows a daily cycle that is largely determined by the hours of light and dark.





The image left shows a scanning electron micrograph (SEM) of a single stoma from the leaf epidermis of a dicot. Note the guard cells (G), which are swollen tight and open the pore (S) to allow gas exchange between the leaf tissue and the external environment.

Factors influencing stomatal opening

Stomata	Guard cells	Daylight	CO_2	Soil water
Open	Turgid	Light	Low	High
Closed	Flaccid	Dark	High	Low

The opening and closing of stomata depends on environmental factors, the most important being light, CO_2 concentration in the leaf tissue, and water supply. Stomata tend to open during daylight in response to light, and close at night (left and above). Low CO_2 levels also promote stomatal opening. Conditions that induce water stress cause the stomata to close, regardless of light or CO_2 level.

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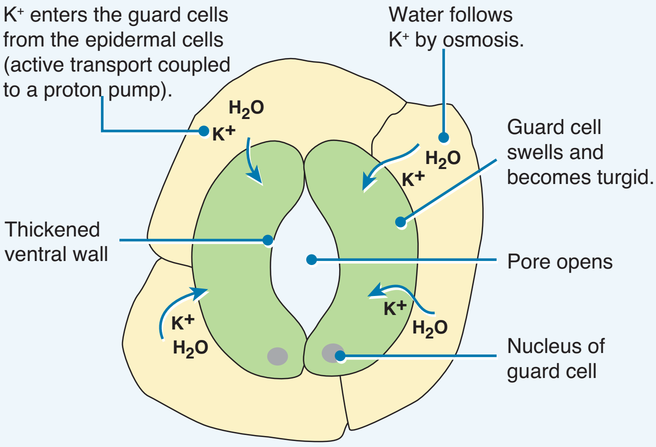
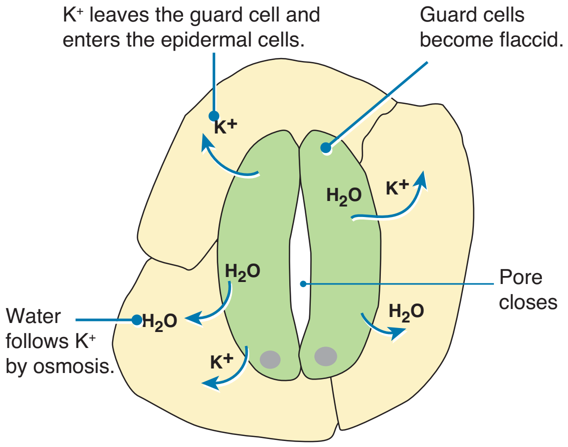
The guard cells on each side of a stoma control the diameter of the pore by changing shape. When the guard cells take up water by osmosis they swell and become turgid, opening the pore. When the guard cells lose water, they become flaccid and the pore closes. By this mechanism a plant can control the amount of gas entering, or water leaving, the plant. The changes in turgor pressure that open and close the pore result mainly from the reversible uptake and loss of potassium ions (and thus water) by the guard cells.

Stomatal pore open



Potassium and water enter the guard cells
Stomata open when the guard cells actively take up K^+ from the neighbouring epidermal cells. As a consequence, water enters the cell by osmosis and they swell and become turgid. The walls of the guard cells are thickened more on the inside surface (the ventral wall) than the outside wall, so that when the cells swell they buckle outward, opening the pore.

Stomatal pore closed



Potassium and water leave the guard cells:
Stomata close when K^+ leaves the guard cells. As a consequence of K^+ outflow from the guard cells, water is lost by osmosis and the cells sag together and close the pore. This process is stimulated by the hormone ABA (abscisic acid), which is synthesised in response to water stress. This response helps to reduce water loss.

1. Describe two adaptive features of leaves:

   (a) ____________________

   (b) ____________________

2. For a terrestrial flowering plant, with no special adaptations for water conservation (a mesophyte):

   (a) Describe the **net** gas exchanges between the air and the cells of the mesophyll in the dark (no photosynthesis):

   ____

   (b) Explain how this situation changes when a plant is photosynthesising: ____________________

   ____

3. Describe two ways in which the continuous air spaces through the plant facilitate gas exchange:

   (a) ____________________

   (b) ____________________

4. Outline the role of stomata in gas exchange in a flowering plant: ____________________

   ____

5. (a) Explain how the guard cells open the stomata: ____________________

   ____

   ____

   ____

   (b) Explain how the guard cells close the stomata: ____________________

   ____

   ____

   ____

ISBN: 978-1-927309-83-4

114 Conditions for Photosynthesis

Key Idea: Photosynthesis requires light to proceed. It produces glucose molecules, which are stored as starch.

Photosynthesis produces glucose which is stored in plant leaves as granules of starch (a glucose polymer) within the photosynthesising cells. In most plants, the leaves are green due to the presence of chloroplasts. In some plants (often those labelled as ornamentals) the leaves can be variegated and carry white or often red patches. Sometimes the entire leaf can be red (e.g. Japanese maples). How does this affect the production of starch in the leaf?

The vast majority of plants have green leaves or stems. The green colour comes from the chlorophyll pigment, which absorbs red and blue light and reflects green (A). Some plants have white patches on the leaves (B) while others may have other colours, most commonly red (C).

Testing for starch

Students investigated photosynthesis in the three types of leaves above (A, B, C) in an experiment outlined below:

- Three plants A, B, C, (as above) were placed in darkness for 48 hours. One leaf (L) was then removed from plant A.
- Several leaves from each plant were then covered with aluminum foil to block the light and the plants were placed back into the light for 24 hours.
- During this time, leaf L was placed into a test tube containing ethanol at its boiling point for ten minutes to remove any pigments from the leaf. This produced a white leaf. The leaf was then placed back into hot water for 20 seconds to soften it.
- Leaf L was tested for starch by applying iodine solution. The applied solution remained brown indicating the absence of starch.
- After 24 hours, a covered and uncovered leaf from each plant was randomly selected. Each leaf was tested for the presence of starch as described above.
- The results are shown below


Plant with foil covered leaves

Iodine test result		
Plant	**Uncovered leaf**	**Covered leaf**
A	Intense blue/black over all leaf	Applied solution remains brown
B	Less intense blue/black over most of the leaf. More intense near centre.	Applied solution remains brown
C	Intense blue/black over middle regions of leaf. Brown on outer edges	Applied solution remains brown

1. Explain the results found in each plant:

   (a) A: ______________________________

   (b) B: ______________________________

   (c) C: ______________________________

2. Why was leaf L tested for starch immediately after removing the plant from the dark? ______________________________

3. What two things does the experiment show the plants need for photosynthesis (as shown by the production of starch):

____

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115 Xylem

Key Idea: The xylem is involved in water and mineral transport in vascular plants.

Xylem is the principal water conducting tissue in vascular plants. It is also involved in conducting dissolved minerals and in supporting the plant body. As in animals, tissues in plants are groupings of different cell types that work together for a common function. In flowering plants, xylem tissue is composed of five cell types: tracheids, vessels, xylem parenchyma, sclereids (short sclerenchyma cells), and fibres. The tracheids and vessel elements form the bulk of the tissue. They are heavily strengthened and are the conducting cells of the xylem. Parenchyma cells are involved in storage, while fibres and sclereids provide support. When mature, xylem is dead.

1. (a) What cells conduct the water in xylem?

____

____

(b) What other cells are present in xylem tissue and what are their roles?

____

____

____

____

____

2. (a) How does water pass between vessels?

____

____

____

(b) How does water pass between tracheids:

____

____

(c) Which cell type do you think provides the most rapid transport of water and why?

____

____

____

(d) Why do you think the tracheids and vessel elements have/need secondary thickening?

____

____

____

____

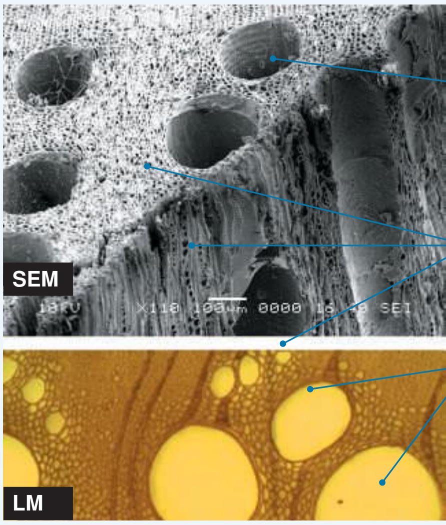
3. How can xylem vessels and tracheids be dead when mature and functional?

____

____

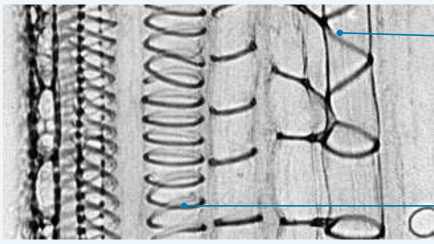
____

____

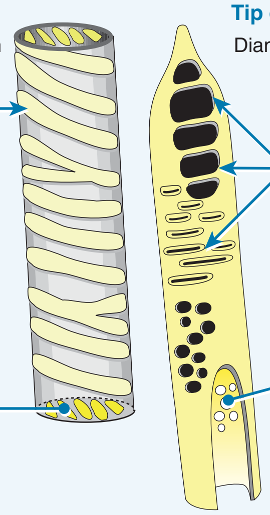


Photos: McKDandy cc 2.5

As shown in these SEM and light micrographs of xylem, the **tracheids** and **vessel elements** form the bulk of the xylem tissue. They are heavily strengthened and are involved in moving water through the plant. The transporting elements are supported by parenchyma (packing and storage cells) and sclerenchyma cells (fibres and sclereids), which provide mechanical support to the xylem.



RCN



Vessel elements and tracheids are the two water conducting cell types in the xylem of flowering plants. Tracheids are long, tapering hollow cells. Water passes from one tracheid to another through thin regions in the wall called pits. Vessel elements are much larger cells with secondary thickening in different patterns (e.g. spirals). Vessel end walls are perforated to allow efficient conduction of water.

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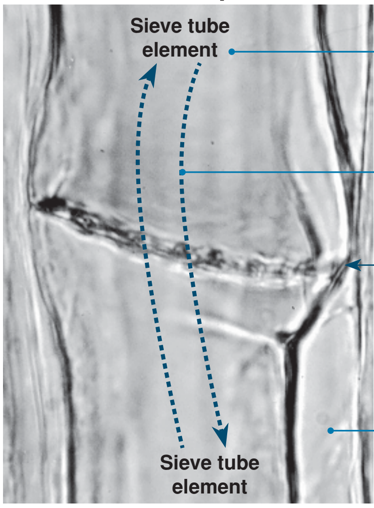
116 Phloem

Key Idea: Phloem is the principal food (sugar) conducting tissue in vascular plants, transporting dissolved sugars around the plant.

Like xylem, **phloem** is also a complex tissue, made up of a variable number of cell types. The bulk of phloem tissue is made up of the **sieve tubes** (sieve tube elements and sieve cells) and their companion cells. The sieve tubes are the main conducting cells in phloem and are closely associated with the **companion cells** which support them. Parenchyma cells, concerned with storage, occur in phloem, and strengthening fibres and sclereids (short sclerenchyma cells) may also be present. Unlike xylem, phloem is alive when mature.

LS through a sieve tube end plate



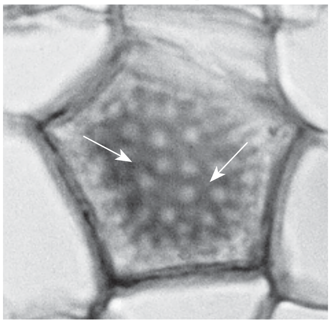
The sieve tube elements (also called sieve tube members) lose most of their organelles but are still alive when mature.

Sugar solution flows in both directions

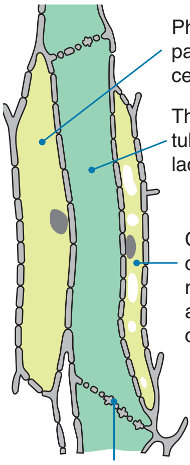
Sieve tube end plate
Tiny holes (arrowed in the photograph below) perforate the sieve tube elements allowing the sugar solution to pass through.

Companion cell
A cell adjacent to the sieve tube member, responsible for keeping it alive.

TS through a sieve tube end plate



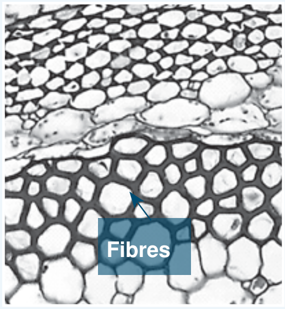
Adjacent sieve tube elements are connected through **sieve plates** through which phloem sap flows.



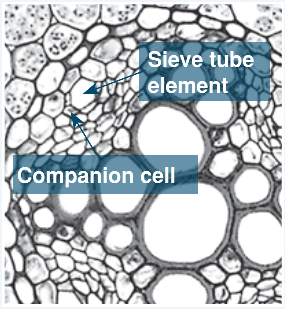
The structure of phloem tissue

Phloem is alive at maturity and functions in the transport of sugars and minerals around the plant. Like xylem, it forms part of the structural vascular tissue of plants.

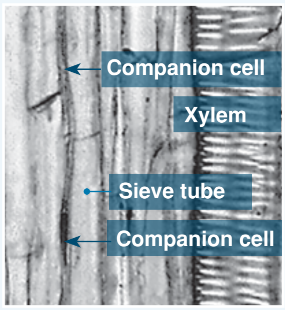
Fibres are associated with phloem as they are in xylem. Here they are seen in cross section where you can see the extremely thick cell walls and the way the fibres are clustered in groups.



In this cross section through a buttercup root, the smaller companion cells can be seen lying alongside the sieve tube members. It is the sieve tube elements that, end on end, produce the **sieve tubes**. They are the conducting tissue of phloem.



In this longitudinal section of a buttercup root, each sieve tube element has a thin **companion cell** associated with it. Companion cells retain their nucleus and control the metabolism of the sieve tube member next to them. They also have a role in the loading and unloading of sugar into the phloem.



1. (a) What is the conducting cell type in phloem? ______________________

   (b) What other cell type is associated with these conducting cells? ______________________

   (c) Describe two roles of these associated cells: ______________________

   ____

2. Mature phloem is a live tissue, whereas xylem (the water transporting tissue) is dead when mature. Why is it necessary for phloem to be alive to be functional, whereas xylem can function as a dead tissue?

   ____

3. What is the role of fibres and sclereids in phloem? ______________________

   ____

4. What are the large open cells next to the phloem in the centre photo above right? ______________________

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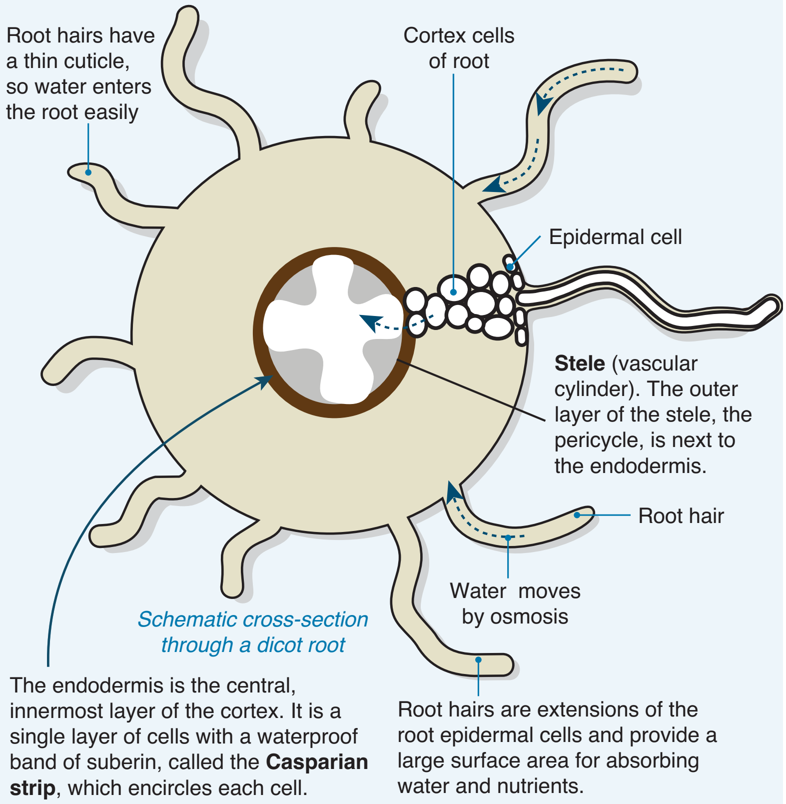
117 Uptake at the The Root

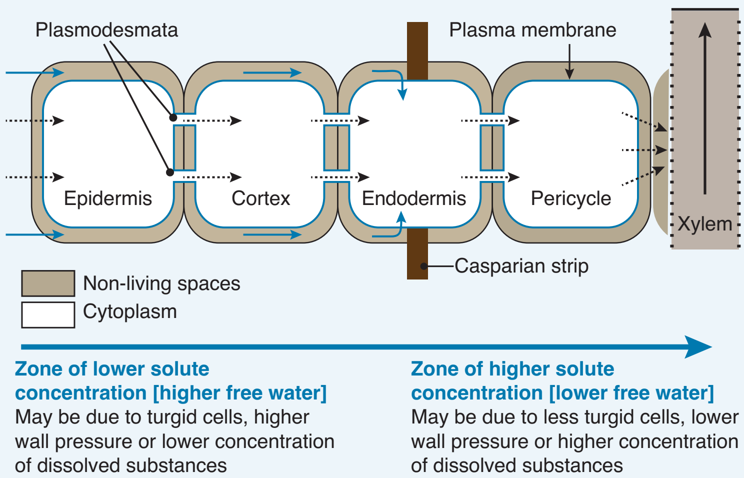
Key Idea: Water uptake by the root is a passive process. Mineral uptake can be passive or active.

Plants need to take up water and minerals constantly. They must compensate for the continuous loss of water from the leaves and provide the materials the plant needs to make food. The uptake of water and minerals is mostly restricted to the younger, most recently formed cells of the roots and the root hairs. Water uptake occurs by osmosis, whereas mineral ions enter the root by diffusion and active transport. Pathways for water movements through the plant are outlined below.

Water and mineral uptake by roots



Paths for water movement through the plant



The uptake of water through the roots occurs by osmosis, i.e. the diffusion of water from a lower solute concentration to a higher solute concentration. Most water travels through the non-living spaces within the cellulose cell walls, the water-filled spaces of dead cells, and the hollow tubes of xylem. Smaller amounts move through the cytoplasm of cells and the plant vacuoles.

Some dissolved mineral ions enter the root passively with water. Minerals that are in very low concentration in the soil are taken up by active transport. At the waterproof Casparian strip, water and dissolved minerals must pass into the cytoplasm, so the flow of materials into the stele can be regulated.

1. (a) What two mechanisms do plants use to absorb nutrients?

   (b) Describe the two main pathways by which water moves through a plant:

2. Plants take up water constantly to compensate for losses due to transpiration. Describe a benefit of a large water uptake:

3. (a) How does the Casparian strip affect the route water takes into the stele?

   (b) Why might this feature be an advantage in terms of selective mineral uptake?

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118 Transpiration

Key Idea: Water moves through the xylem primarily as a result of evaporation from the leaves and the cohesive and adhesive properties of water molecules.

Plants lose water all the time. Approximately 99% of the water a plant absorbs from the soil is lost by evaporation from the leaves and stem. This loss, mostly through stomata, is called **transpiration** and the flow of water through the plant is called the **transpiration stream**. Plants rely on a gradient in solute concentration that increases from the roots to the air to move water through their cells. Water flows passively from soil to air along this gradient of increasing solute concentration. The gradient is the driving force for the movement of water up a plant. Transpiration has benefits to the plant because evaporative water loss cools the plant and the transpiration stream helps the plant to take up minerals. Factors contributing to water movement are described below.

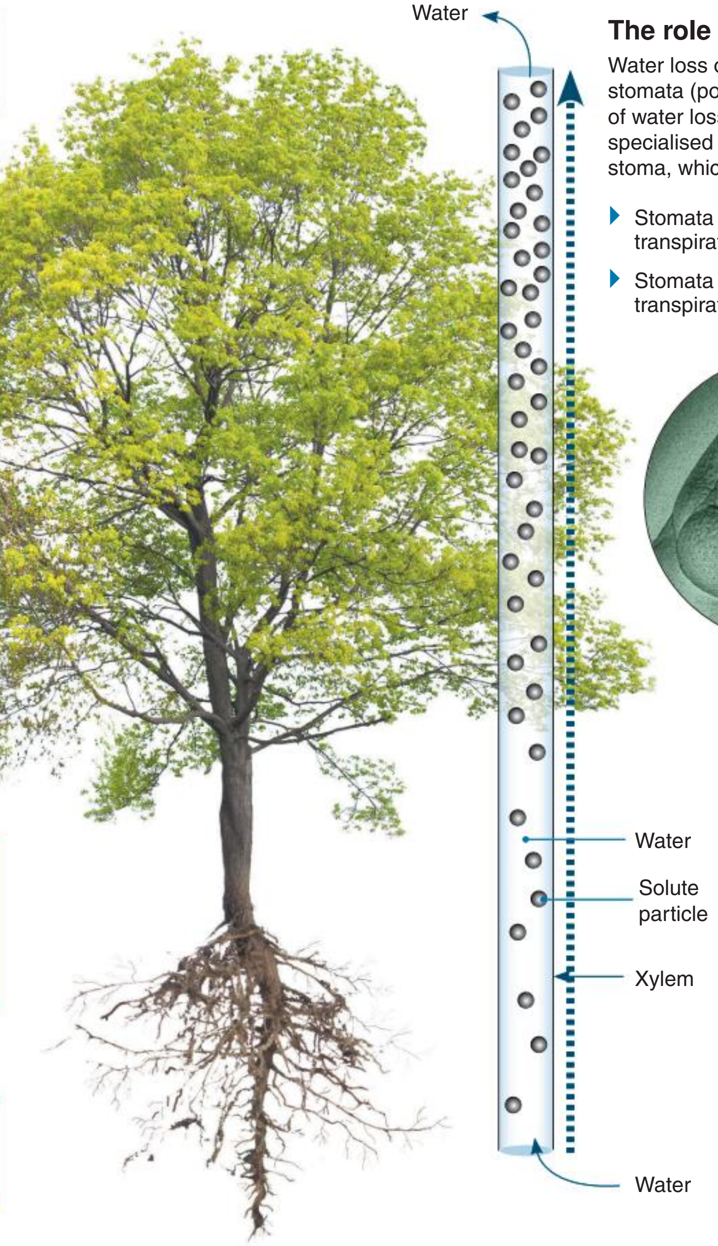
Air
Evaporative loss of water from the leaves as water vapour

Leaves
Highest solute concentration
Lowest water concentration

Water flows passively from a low solute concentration (high water concentration) to a high solute concentration (lower water concentration). This gradient is the driving force in the transport of water up a plant.

The continuous flow of water is called the **transpiration stream**. It is primarily responsible for water moving up the plant.

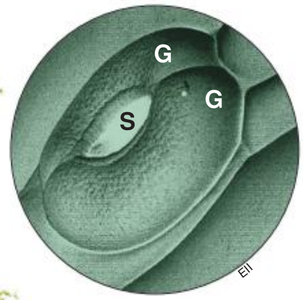
Soil
Highest water concentration
Lowest solute concentration



The role of stomata

Water loss occurs mainly through stomata (pores in the leaf). The rate of water loss can be regulated by specialised guard cells each side of the stoma, which open or close the pore.

- Stomata open: gas exchange and transpiration rate increase.
- Stomata closed: gas exchange and transpiration rates decrease.



1. (a) What is transpiration? ______________________________

____

(b) Describe one benefit of the transpiration stream for a plant: ______________________________

____

____

____

2. How does the plant regulate the amount of water lost from the leaves? ______________________________

____

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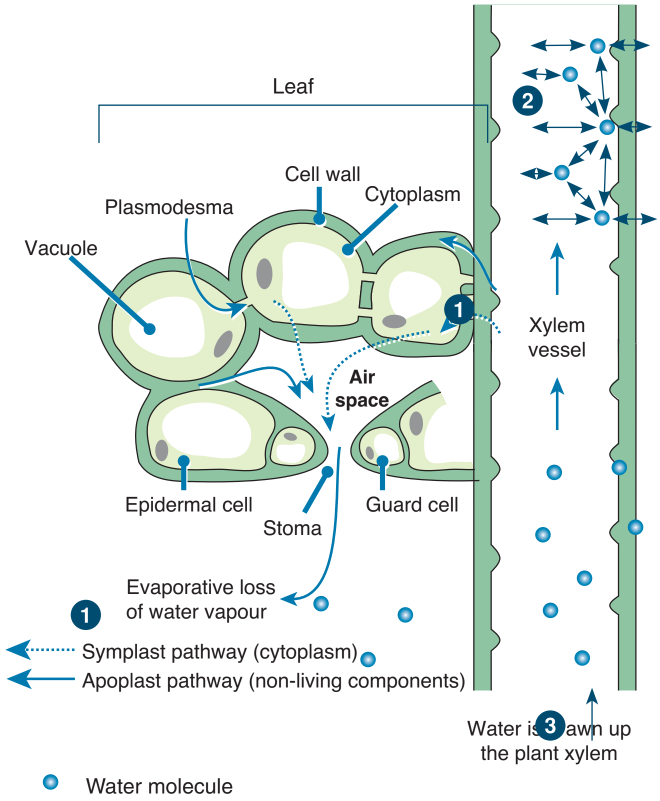
Processes involved in moving water through the xylem

1 Transpiration pull
Water is lost from the air spaces by evaporation through stomata and is replaced by water from the mesophyll cells. The constant loss of water to the air (and production of sugars) creates a solute concentration in the leaves that is higher than elsewhere in the plant. Water is pulled through the plant along a **gradient of increasing solute concentration**.

2 Cohesion-tension
The transpiration pull is assisted by the special **cohesive** properties of water. Water molecules cling together as they are pulled through the plant. They also **adhere** to the walls of the xylem (**adhesion**). This creates one **unbroken column of water** through the plant. The upward pull on the cohesive sap creates a tension (a negative pressure). This helps water uptake and movement up the plant.

3 Root pressure
Water entering the stele from the soil creates a **root pressure**; a weak 'push' effect for the water's upward movement through the plant. Root pressure can force water droplets from some small plants under certain conditions (**guttation**), but generally it plays a minor part in the ascent of water.



3. (a) What would happen if too much water was lost from the leaves? ______________________

____

(b) When might this happen? ______________________

4. Describe the three processes that assist the transport of water from the roots of the plant upward:

(a) ______________________

____

____

____

(b) ______________________

____

____

(c) ______________________

____

____

5. The maximum height water can move up the xylem by cohesion-tension alone is about 10 m. How then does water move up the height of a 40 m tall tree?

____

____

____

____

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119 Investigating Plant Transpiration

Key Idea: The relationship between the rate of transpiration and the environment can be investigated using a potometer.

This activity describes a typical experiment to investigate the effect of different environmental conditions on transpiration rate using a potometer. You will present and analyse the results provided.

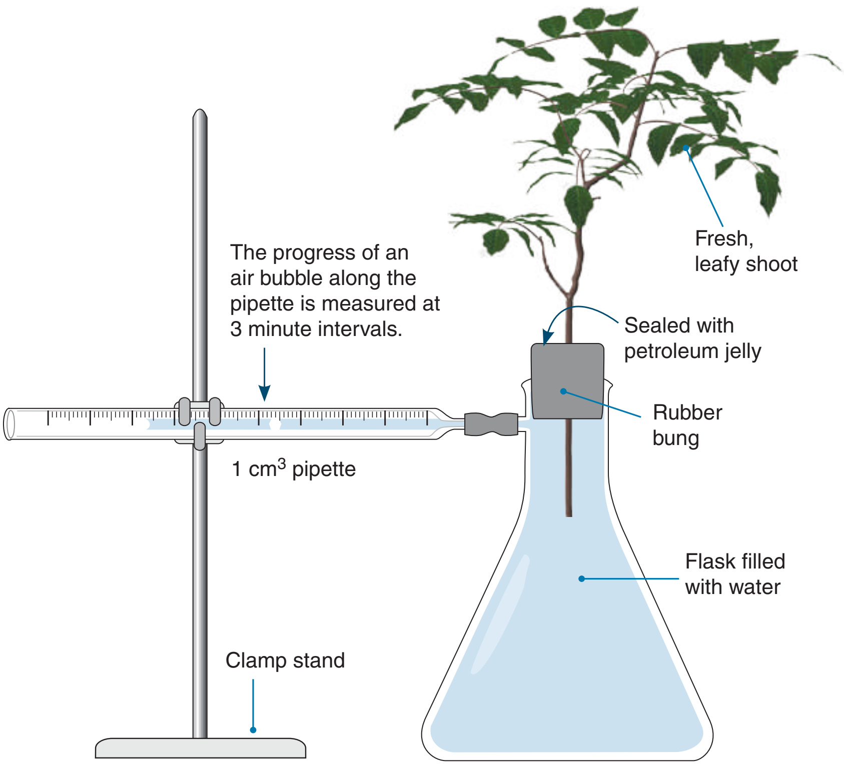
The potometer

A potometer is a simple instrument for investigating transpiration rate (water loss per unit time). The equipment is simple to use and easy to obtain. A basic potometer, such as the one shown right, can easily be moved around so that transpiration rate can be measured under different environmental conditions.

Some physical conditions investigated are:

- Humidity or vapour pressure (high or low)
- Temperature (high or low)
- Air movement (still or windy)
- Light level (high or low)
- Water supply

It is also possible to compare the transpiration rates of plants with different adaptations e.g. comparing transpiration rates in plants with rolled leaves vs rates in plants with broad leaves. If possible, experiments like these should be conducted simultaneously using replicate equipment. If conducted sequentially, care should be taken to keep the environmental conditions the same for all plants used.



The aim

To investigate the effect of environmental conditions on the transpiration rate of plants.

Background

Plants lose water all the time by evaporation from the leaves and stem. This loss, mostly through pores in the leaf surfaces, is called **transpiration**. Despite the adaptations plants have to help prevent water loss (e.g. waxy leaf cuticle), 99% of the water a plant absorbs from the soil is lost by evaporation. Environmental conditions can affect transpiration rate by increasing or decreasing the gradient for diffusion of water molecules between the plant and its external environment.

The apparatus

This experiment investigated the influence of environmental conditions on plant transpiration rate. The experiment examined four conditions: room conditions (ambient), wind, bright light, and high humidity. After setting up the potometer, the apparatus was equilibrated for 10 minutes, and then the position of the air bubble in the pipette was recorded. This is the time 0 reading. The plant was then exposed to one of the environmental conditions. Students recorded the location of the air bubble every three minutes over a 30 minute period. The potometer readings for each environmental condition are presented in Table 1 (next page).

A class was divided into four groups to study how four different environmental conditions (ambient, wind, bright light, and high humidity) affected transpiration rate. A **potometer** was used to measure transpiration rate (water loss per unit time). A basic potometer, such as the one shown left, can easily be moved around so that transpiration rate can be measured under different environmental conditions.

4

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Table 1. Potometer readings (in mL water loss)

Treatment \ Time (min)	0	3	6	9	12	15	18	21	24	27	30
Ambient	0	0.002	0.005	0.008	0.012	0.017	0.022	0.028	0.032	0.036	0.042
Wind	0	0.025	0.054	0.088	0.112	0.142	0.175	0.208	0.246	0.283	0.325
High humidity	0	0.002	0.004	0.006	0.008	0.011	0.014	0.018	0.019	0.021	0.024
Bright light	0	0.021	0.042	0.070	0.091	0.112	0.141	0.158	0.183	0.218	0.239

1. (a) Plot the potometer data from Table 1 on the grid provided:

   (b) Identify the independent variable:

2. (a) Identify the control:

   (b) Explain the purpose of including an experimental control in an experiment:

   (c) Which factors increased water loss?

   (d) How does each environmental factor influence water loss?

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120 Translocation

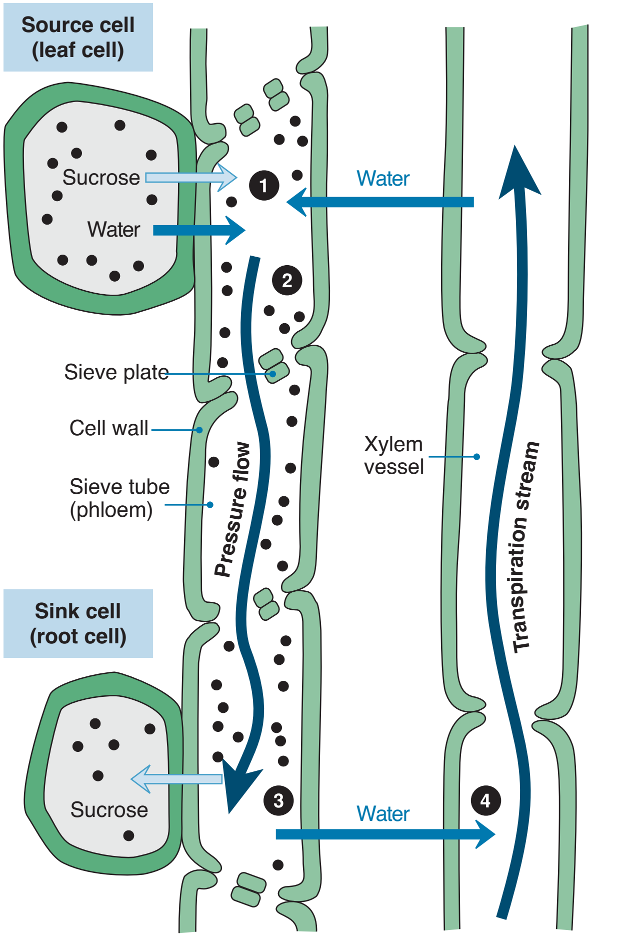
Key Idea: Phloem transports the organic products of photosynthesis (sugars) through the plant by translocation.

In angiosperms, the sugar moves through the phloem sieve-tube members, which are arranged end-to-end and perforated with sieve plates. Apart from water, phloem sap contains mainly sucrose (up to 30%). It may also contain minerals, hormones, and amino acids in transit around the plant. Movement of sap in the phloem is from a **source** (a plant organ where sugar is made or mobilised) to a **sink** (a plant organ where sugar is stored or used). Loading sucrose into the phloem at a source involves energy expenditure. We know this because it is slowed or stopped by high temperatures or respiratory inhibitors. In some plants, unloading the sucrose at the sinks also requires energy, although in others, diffusion alone is sufficient to move sucrose from the phloem into the cells of the sink organ.

Phloem transport

Phloem sap moves from source to sink at rates as great as 100 m h^{-1}, which is too fast to be accounted for by cytoplasmic streaming. The most acceptable model for phloem movement is the **mass flow hypothesis** (also know as the pressure flow hypothesis). Phloem sap moves by bulk flow, which creates a pressure (hence the term "pressure-flow"). The key elements in this model are outlined below and right. For simplicity, the cells that lie between the source (and sink) cells and the phloem sieve-tube have been omitted.

1. Loading sugar into the phloem increases the solute concentration inside the sieve-tube cells. This causes the sieve-tubes to take up water by osmosis.
2. The water uptake creates a hydrostatic pressure that forces the sap to move along the tube, just as pressure pushes water through a hose.
3. The pressure gradient in the sieve tube is reinforced by the active unloading of sugar and consequent loss of water by osmosis at the sink (e.g. root cell).
4. Xylem recycles the water from sink to source.



Source: Modified after Campbell *Biology* 1993

Measuring phloem flow

Aphids can act as natural phloem probes to measure phloem flow. The sucking mouthparts (stylet) of the insect penetrates the phloem sieve-tube cell. While the aphid feeds, it can be severed from its stylet, which remains in place and continues to exude sap. Using different aphids, the rate of flow of this sap can be measured at different locations on the plant.

1. (a) From what you know about osmosis, explain why water follows the sugar as it moves through the phloem:

(b) What is meant by '**source to sink**' flow in phloem transport?

2. Why does a plant need to move food around, particularly from the leaves to other regions?

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121 KEY TERMS AND IDEAS: Did You Get It?

1. (a) What is the name given to the loss of water vapour from plant leaves and stems? ______________

   (b) What plant tissue is involved in this process? ______________

   (c) Is this tissue alive or dead? ______________

   (d) Does this process require energy? ______________

2. Match each term to its definition, as identified by its preceding letter code.

Term		Definition
cohesion-tension	A	Device used for investigating the rate of transpiration.
guard cells	B	The loss of water vapour by plants, mainly from leaves via the stomata.
phloem	C	Specialised cells either side of the stoma, which open or close the pore.
potometer	D	Vascular tissue that conducts water and minerals from the roots to the rest of the plant.
stomata	E	Pores in the leaf surface through which gases and water vapour can pass
transpiration	F	Partial explanation for the movement of water up the plant in the transpiration stream.
xylem	G	Tissue that conducts dissolved sugars in vascular plants. Largely made up of sieve tubes and companion cells.

3. Transpiration in a hydrangea shoot was investigated using a potometer. The experiment was set up and the plant left to stabilise (environmental conditions: still air, light shade, 20°C). The plant was then placed in different environmental conditions and the water loss was measured each hour. Finally, the plant was returned to original conditions, allowed to stabilise and transpiration rate measured again. The results are presented below:

Experimental conditions	Temperature (°C)	Humidity (%)	Transpiration rate (g h^{-1})
(a) Still air, light shade, room temperature	20	70	1.20
(b) Moving air, light shade	20	70	1.60
(c) Still air, bright sunlight	23	70	3.75
(d) Still air and dark, moist chamber	19.5	100	0.05

   (a) What conditions acted as the control in this experiment? ______________

   (b) Which factors increased transpiration rate and why? ______________

   (c) Why did the plant have such a low transpiration rate in humid, dark conditions? ______________

4. The leaf below was left in light for 24 hours then tested for starch. In the space provided draw a diagram of the leaf below to show where you would expect to find starch:

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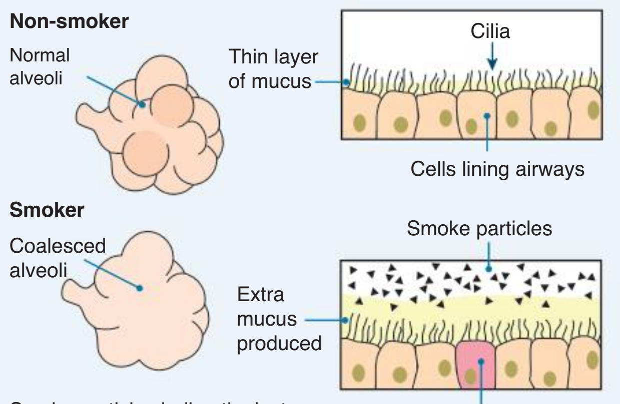
122 Synoptic Question: Unit 1 Topic 2

1. Stem cells have the potential to be an important medical tool for the replacement of damaged or diseased tissue or organs. Explain why stem cells are potentially useful and describe some of the ethical issues associated with their use:

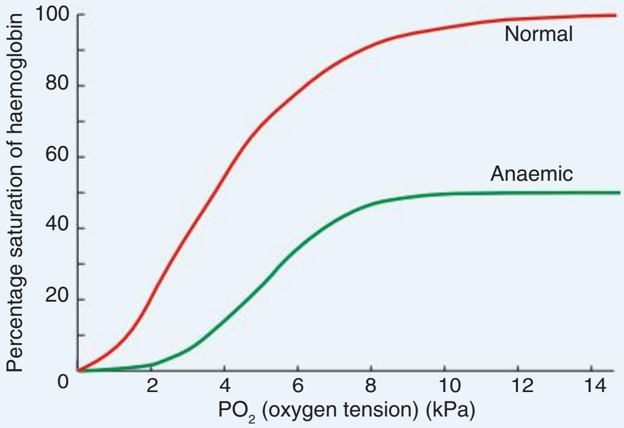
2. Tobacco smoking is a major risk factor in the occurrence of emphysema, chronic bronchitis, and cancers of the respiratory tract. Smoking causes the lung tissue to lose its elasticity and tar from the tobacco smoke clogs the airways and damages the alveoli (right). Use the diagram to help you to explain why smoking reduces the gas exchange capacity of the lung tissue:



Smoke particles indirectly destroy the walls of the lung's alveoli.

3. People with iron-deficient anaemia lack of haemoglobin in the blood. The graph below shows the oxygen-haemoglobin dissociation curves for a person with iron deficient anaemia compared to a person with normal haemoglobin levels.

(a) What does an oxygen-haemoglobin dissociation curve show?



(b) What has happened to the oxygen-haemoglobin dissociation curve in the anaemic person and why?

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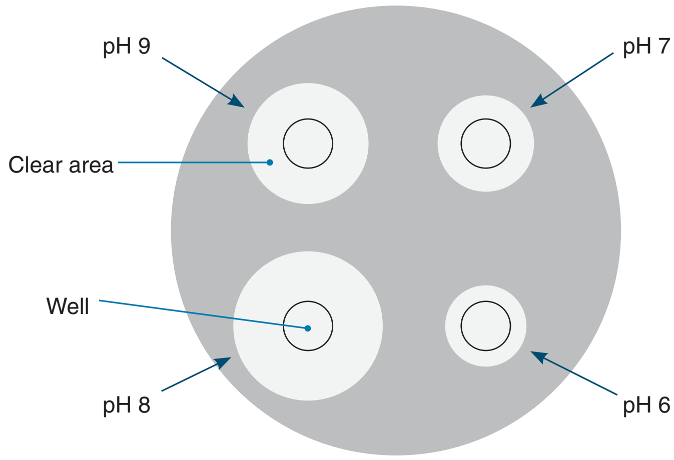
4. A student wanted to investigate the effect of pH on a peptidase (a protease) produced in the small intestine of a human. She used an agar plate containing protein. This made the agar plate cloudy. Digestion of the protein by the peptidase makes the agar clear.
   - The agar plate was made with four equal sized wells into which the peptidase could be added. Four different mixtures of peptidase at different pH where produced and added to the wells.
   - The set up was incubated at a constant temperature for 4 hours.
   - The diagram below shows the results:



(a) Suggest a temperature for incubation of the agar plate for best results: ______

(b) Why did you choose this temperature? ______

______

(c) Which pH produced the best result? ______

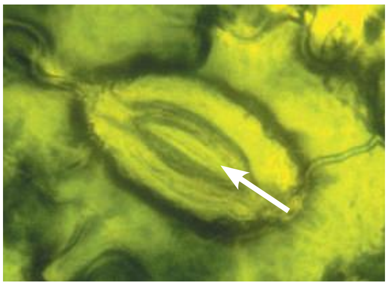
(d) Explain why: ______

______

______

______

5. (a) The photograph shows a structure on a plant leaf. Identify the structure arrowed in the photograph:



______

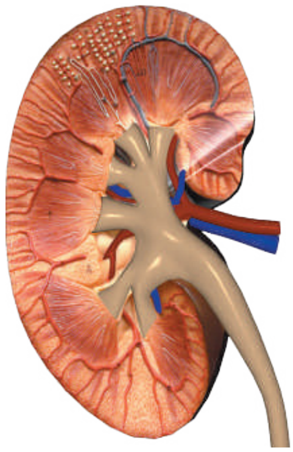
(b) When is this structure likely to be open (day or night)?

______

(c) What happens when the cells surrounding the structure take up water?

______

6. (a) In which region of the kidney would you find the glomeruli? ______



(b) In which region of the kidney would you find the loop of Henle? ______

(c) You would expect a desert-living mammal to have a short/long loop of Henle (delete one)

Explain your choice: ______

______

______

______

______

______

ISBN: 978-1-927309-83-4

UNIT 2
Topic 1

Homeostasis

Key terms

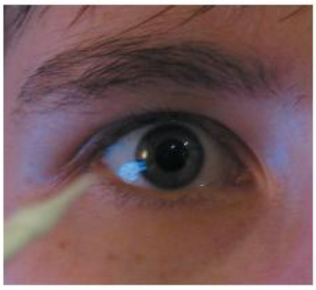
anabolic reaction
catabolic reaction
chemoreceptor
effector
homeostasis
mechanoreceptor
metabolism
negative feedback
nociceptor
optimum
osmoregulation
photoreceptor
positive feedback
proprioception
response
sensory receptor
stimulus (pl. stimuli)
thermoreceptor
thermoregulation
tolerance limit
transducer

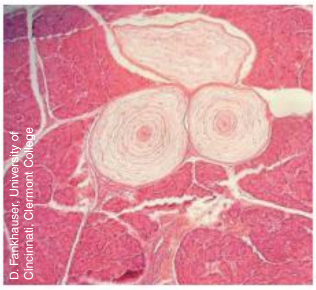
Activity number

Principles of homeostasis

Key skills and knowledge

		Key skills and knowledge	Activity number
☐	1	Know that homeostasis (steady state) involves a stimulus-response model in which change in the internal or external environment (the stimulus) is detected and appropriate responses occur via negative feedback.	123 125 130
☐	2	Describe the role of sensory receptors in detecting stimuli. Classify receptors based on the stimuli to which they respond to include chemoreceptors, photoreceptors, thermoreceptors, mechanoreceptors, and nociceptors.	124
☐	3	Describe the role of effectors (muscles and glands) in bringing about the response to stimuli.	123
☐	4	In more detail than #1 above, use an example to explain how negative feedback stabilises systems against excessive change.	125
☐	5	Using an example, describe positive feedback as a destabilising mechanism with a specific role in certain physiological processes.	126
☐	6	Interpret feedback control diagrams for either nervous or hormonal systems, recognising stimulus, receptor, control centre, effector, and communication pathways. Examples could include thermoregulation, osmoregulation, blood glucose regulation, or proprioception.	125 126 130 141 145 152 160





Metabolism

Key skills and knowledge

		Key skills and knowledge	Activity number
☐	7	Explain what is meant by metabolism. Describe metabolic reactions as either catabolic or anabolic and give examples of each.	127
☐	8	Recall that enzymes have an optimum range of conditions over which they operate most effectively. Explain why changes in metabolic activity alter the optimum conditions for catalytic activity of enzymes (with reference to tolerance limits).	127
☐	9	**PRAC** Investigate tolerance limits for salt balance by testing the effect of salt level on plant growth.	128

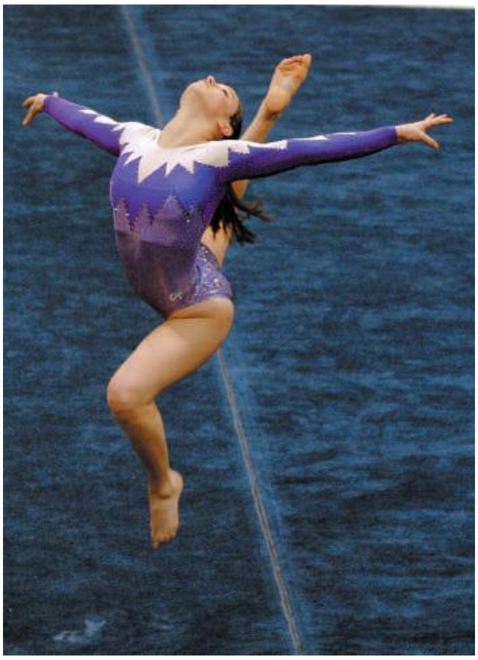
123 Homeostasis

Key Idea: Homeostasis refers to the (relatively) constant physiological state of the body despite fluctuations in the environment.

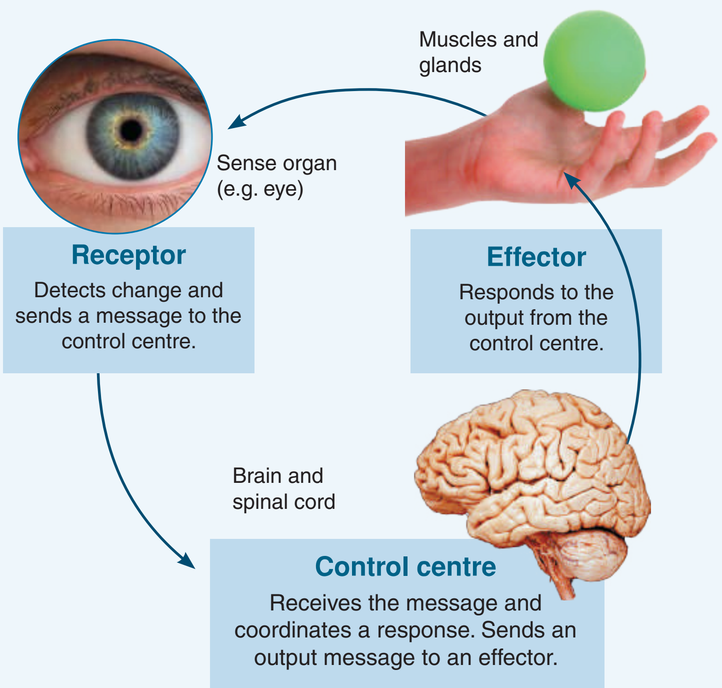
Organisms maintain a relatively constant physiological state, called **homeostasis**, despite changes in their environment. Any change in the environment to which an organism responds is called a **stimulus** and, because environmental stimuli are not static, organisms must also adjust their behaviour and physiology constantly to maintain homeostasis. This requires the coordinated activity of the body's organ systems. Homeostatic mechanisms prevent deviations from the steady state and keep the body's internal conditions within strict limits. Deviations from these limits can be harmful (e.g. by impairing enzyme activity and therefore metabolic pathways).

For example, during exercise (right) body temperature must remain relatively constant at about 37.0°C despite the extra heat generated by activity. You must regulate blood sugar levels and blood pH, water and electrolyte balance, and blood pressure. Your body's organ systems carry out these tasks.

To maintain homeostasis, the body must detect stimuli through receptors, process this sensory information, and respond to it appropriately via effectors. If the effector is a muscle, it results in muscle contraction. If the effector is a gland, it produces a secretion. The responses provide new feedback to the receptor. These three components are illustrated below.



How homeostasis is maintained



The analogy of a thermostat on a heater is a good way to understand how homeostasis is maintained. A heater has sensors (a receptor) to monitor room temperature. It also has a control centre to receive and process the data from the sensors. Depending on the data it receives, the control centre activates the effector (heating unit), switching it on or off. When the room is too cold, the heater switches on. When it is too hot, the heater switches off. This maintains a constant temperature.

1. What is homeostasis? ______________________________

____

2. What is the role of the following components in maintaining homeostasis:

(a) Receptor: ______________________________

____

(b) Control centre: ______________________________

____

(c) Effector: ______________________________

____

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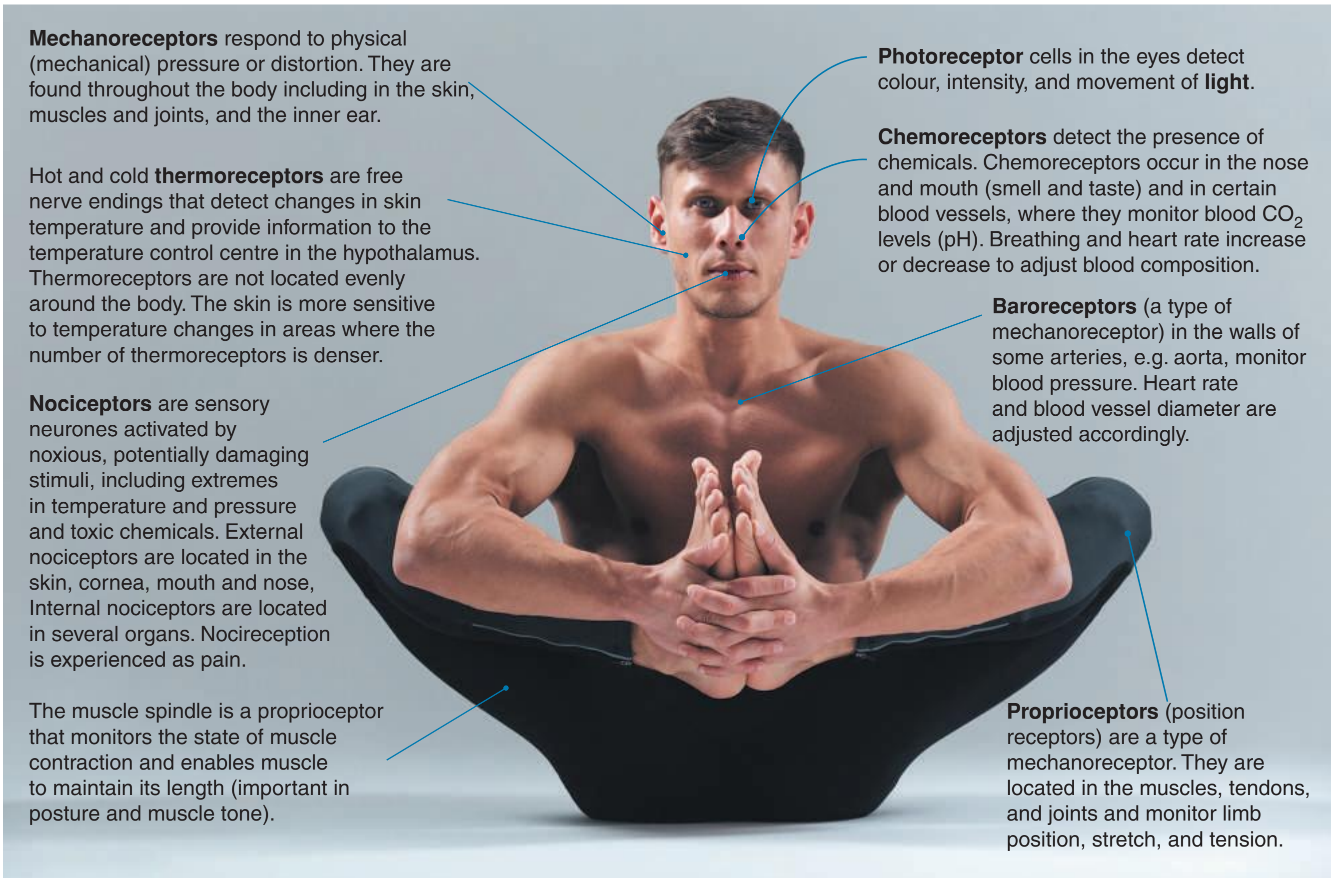
124 Sensory Receptors

Key Idea: Sensory receptors allow the body to respond to a range of stimuli in the internal and external environments.

A stimulus is any physical or chemical change in the environment capable of provoking a response in an organism. Organisms respond to stimuli in order to survive. Stimuli may be either external (outside the organism) or internal (within its body). Some of the sensory receptors that animals use to detect stimuli are shown below. Sensory receptors respond only to specific stimuli, so the sense organs an animal has determines how it perceives the world.



Temperature and pain are detected by nerve endings in the skin. Deep tissue injury is sometimes felt on the skin as referred pain.

Humans rely heavily on hearing when learning to communicate; without it, speech and language development are more difficult.

The vibration receptors in the limbs of arthropods are sensitive to movement: either sound or vibration (from struggling prey).

The chemosensory Jacobson's organ in the roof of the mouth of reptiles (e.g. snakes) enables them to detect chemical stimuli.

Breathing and heart rates are regulated in response to sensory input from internal chemoreceptors.

Baroreceptors and osmoreceptors act together to maintain blood pressure and volume.

bauer

Many insects, such as these ants, rely on chemical sense for location of food and communication.

Stimulation of nociceptors in the eye often cause rapid blinking or watering of the eye to remove the harmful stimulus.

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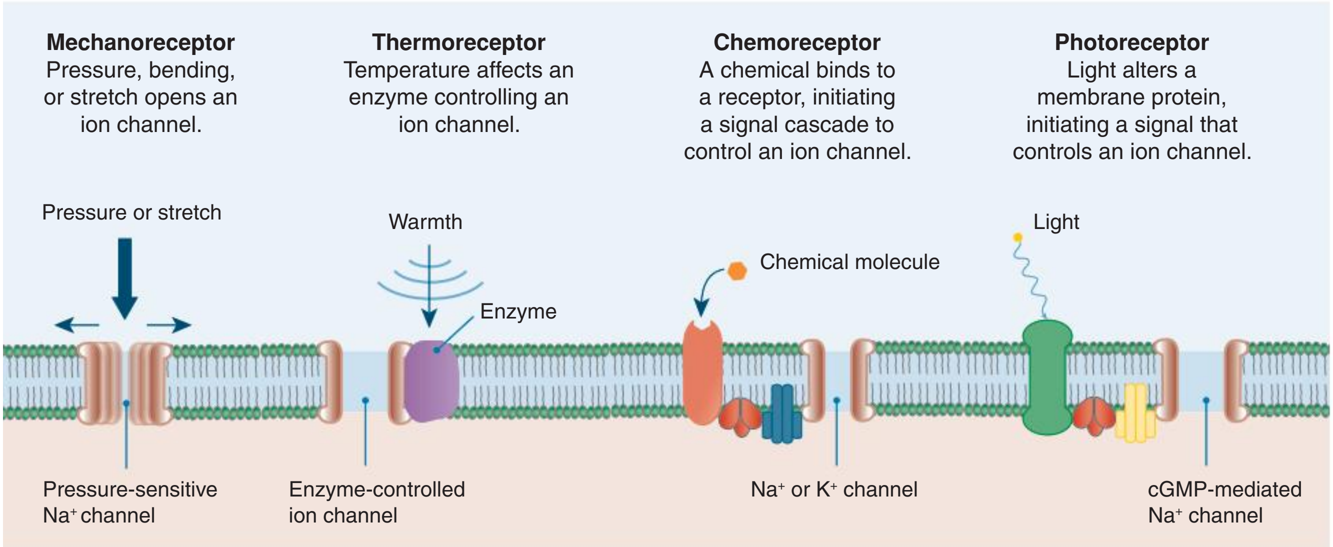
Stimuli activate ion channels

Sensory receptors respond to stimuli by producing an electrical (or chemical) discharge. In this way they act as biological transducers, converting the energy from a stimulus into an electrochemical signal. They can do this because the stimulus opens (or closes) ion channels and leads to localised changes in membrane potential called receptor potentials. These receptor potentials lead to nerve impulses, which can then be interpreted by the central nervous system (e.g. as pain, light, smell etc). The membrane potential is the difference in the concentrations of ions on opposite sides of a cellular membrane. The diagram below shows the four types of ion channels activated in stimulated receptors.

D. Fankhauser, University of Cincinnati, Clermont College

The Pacinian corpuscle

Pacinian corpuscles (left) are pressure receptors in the deep tissues of the body. They are relatively large but structurally simple, consisting of a sensory nerve ending (dendrite) surrounded by a capsule of connective tissue layers. Pressure deforms the capsule, stretching the nerve ending and leading to a receptor potential and then a nerve impulse. This is interpreted by the central nervous system as pressure.



1. What is a stimulus? ______________________________

____

2. Why is it important for an organism to be able to respond to a stimuli? ______________________________

____

____

3. Decide if the following stimuli are internal and/or external and name the type of receptor involved in its detection:

(a) Light: ______________________________

(b) Blood pH: ______________________________

(c) Degree of muscle stretch: ______________________________

(d) Temperature: ______________________________

(e) Pain: ______________________________

(f) Body position: ______________________________

4. Explain how sensory receptors act as biological transducers and why this is important: ______________________________

____

____

____

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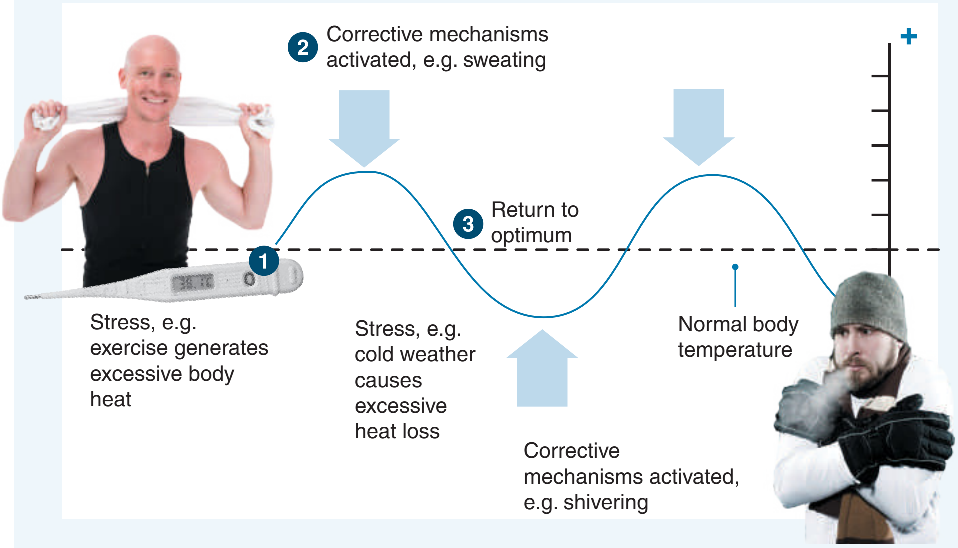
125 Negative Feedback

Key Idea: Negative feedback mechanisms detect departures from a desired set point and act to restore the steady state.

Negative feedback is a regulatory mechanism that maintains the body's homeostasis by detecting deviations from a certain set point and acting to restore those set point conditions. Negative feedback mechanisms act to dampen variations and so have a stabilising effect on biological systems. Most body systems achieve homeostasis through negative feedback. Body temperature, blood glucose levels, and blood pressure are all controlled by negative feedback mechanisms.

Negative feedback in temperature regulation

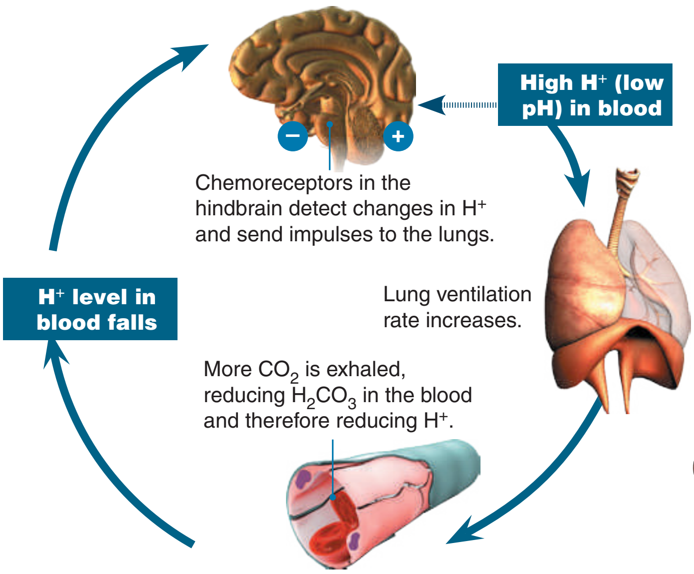


The diagram (left) shows how temperature is regulated by negative feedback mechanisms.

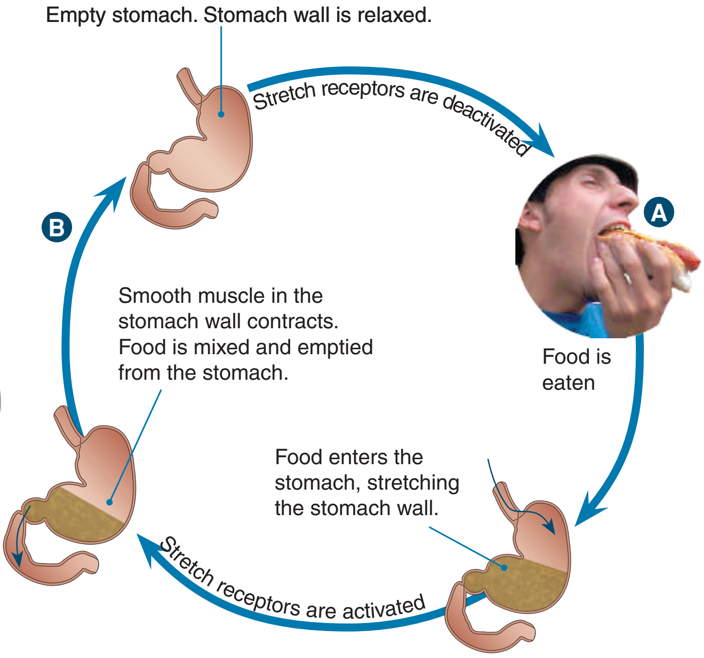
1. A **stressor**, e.g. exercise, takes the internal environment away from optimum.
2. Stress is detected by receptors and corrective mechanisms (e.g. sweating or shivering) are activated.
3. Corrective mechanisms act to restore optimum conditions.

Negative feedback in blood pH

Regulation of ventilation rate helps to maintain blood pH between 7.35 and 7.45. Low blood pH stimulates increased breathing rate, which reduces H^+ via exhalation. This reduces sensory input to the medulla and breathing returns to normal.



Negative feedback in stomach emptying



1. How do negative feedback mechanisms maintain homeostasis in a variable environment? ______________________

____

____

2. On the diagram of stomach emptying:

(a) State the stimulus at A: ______________ State the response at B: ______________

(b) Name the effector in this system: ______________________

(c) What is the steady state for this example? ______________________

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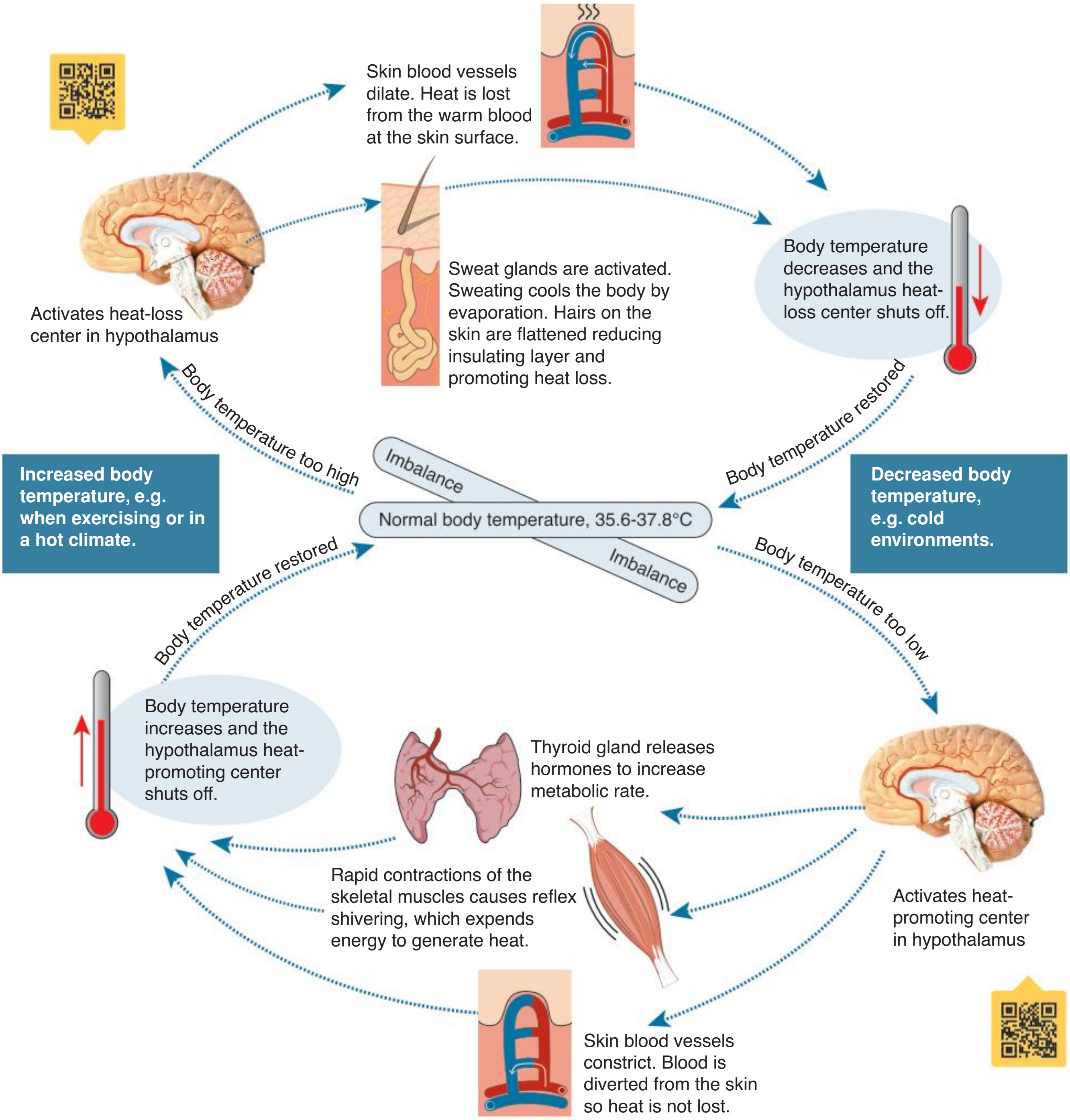
How is body temperature regulated?

- In humans, the temperature regulation centre is a region of the brain called the **hypothalamus**. It has thermoreceptors that monitor core body temperature and has a 'set-point' temperature of 36.7°C.
- The hypothalamus acts like a thermostat. It registers changes in the core body temperature and also receives information about temperature changes from thermoreceptors in the skin. It then coordinates nervous and hormonal responses to counteract the changes and restore normal body temperature, as shown in the feedback diagram below. When normal temperature is restored, the corrective mechanisms are switched off.



3. In the diagram above showing the regulation of body temperature:

   (a) Identify the stimulus: ______________________________

   (b) Identify the control centre: ______________________________

   (c) Identify the effectors: ______________________________

4. How do the effectors restore body temperature when it increases above the set point? ______________________________

____

____

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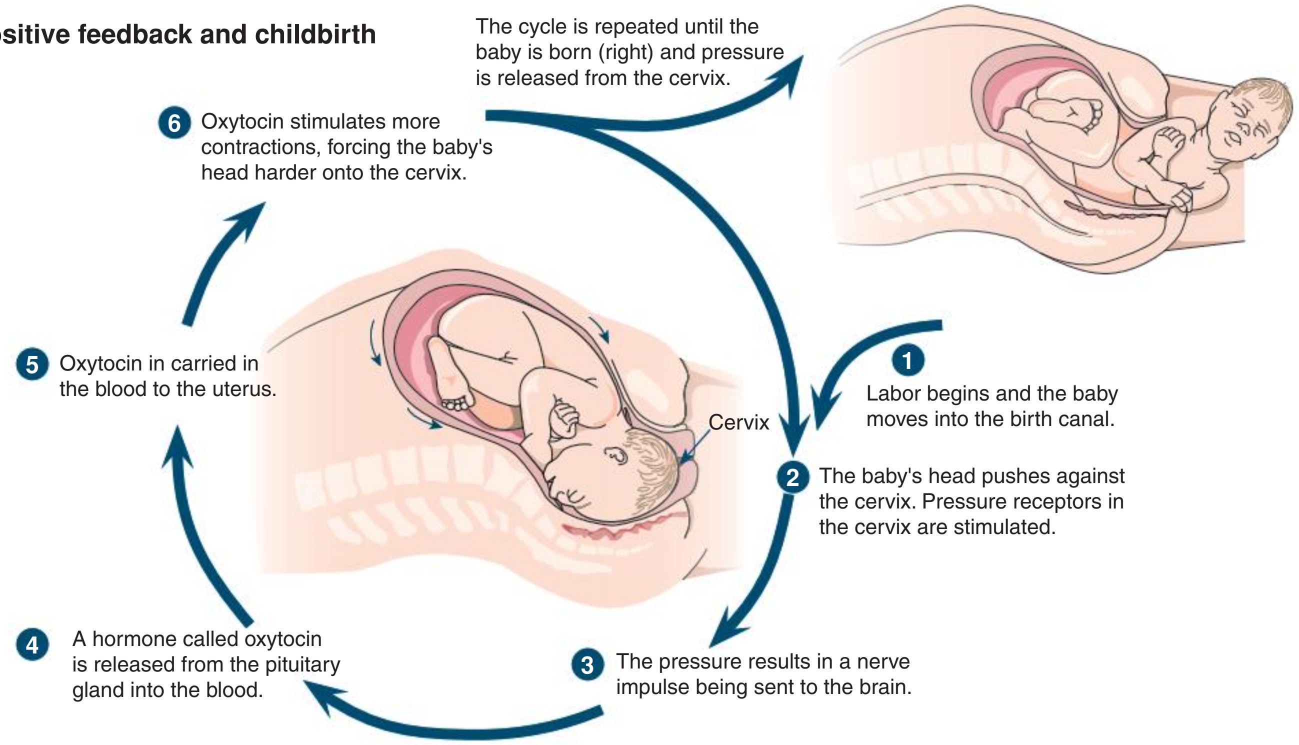
126 Positive Feedback

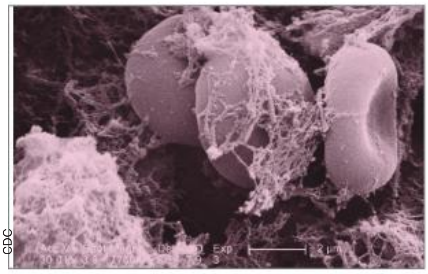
Key Idea: Positive feedback mechanisms in biological systems amplify a response to achieve a particular outcome.

In contrast to negative feedback, positive feedback mechanisms amplify (increase) a response in order to achieve a particular result. Examples include fruit ripening, fever, blood clotting, childbirth (labour) and lactation (production of milk).

A positive feedback mechanism stops when the end result is achieved (e.g. the baby is born, a pathogen is destroyed by a fever, or ripe fruit falls off a tree). Positive feedback is less common than negative feedback in biological systems because the escalation in response is unstable. Unresolved positive feedback responses (e.g. high fevers) can be fatal.

Positive feedback and childbirth





CDC

Positive feedback also occurs in **blood clotting**. A wound releases signal chemicals that activate platelets in the blood. Activated platelets release chemicals that activate more platelets, so a blood clot is rapidly formed.

Ragesoss

Ethylene is a gaseous plant hormone involved in fruit ripening. It accelerates the ripening of fruit in its vicinity so nearby fruit also ripens, releasing more ethylene. Over-exposure to ethylene causes fruit to over-ripen (rot).

Infection can reset the set-point of the hypothalamus to a higher temperature. The body temperature then increases above the normal range, resulting in a fever. Fever is an important defence against infection.

1. (a) Why is positive feedback much less common than negative feedback in body systems? ____________________

____

____

(b) Why can positive feedback be dangerous if it continues on for too long? ____________________

____

____

(c) How is a positive feedback loop normally stopped? ____________________

____

(d) Predict what could happen if a person's temperature increased uncontrollably during a fever? ____________________

____

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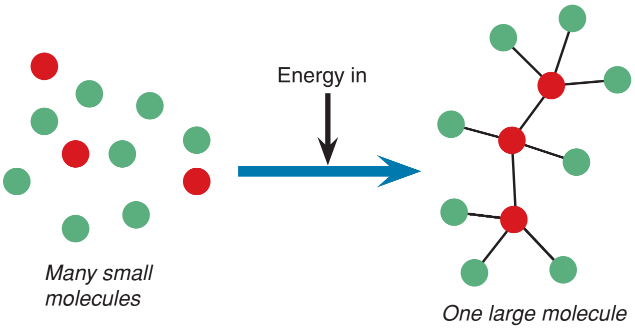
127 Metabolism and Life

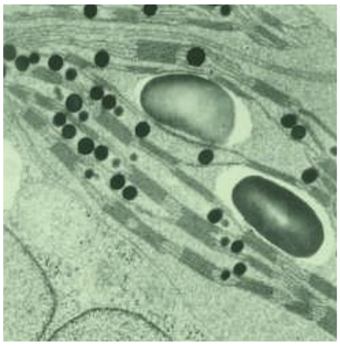
Key Idea: Enzymes catalyse all of the body's metabolic reactions. Homeostasis helps to maintain the physiological conditions required for optimum enzyme activity.

Metabolism is defined as all the chemical processes occurring within a living organism to maintain life. Enzymes catalyse each of these metabolic reactions. Recall that enzymes have a narrow range of physical conditions for optimum activity. Regional specialisation within the body or its cells helps to provide these conditions. Outside the optimum range, enzyme activity drops off or stops. When this occurs, metabolic pathways are impaired and there are detrimental or even fatal effects on the organism. For example, acidosis is a condition in which blood pH falls. Enzyme activity is impaired and this depresses organ function. Homeostasis maintains narrow physiological conditions, such as pH, so that metabolic reactions can proceed normally.

Anabolic reactions

- **Anabolic reactions** are reactions that result in the production (synthesis) of a more complex molecule from smaller components or smaller molecules. During anabolic reactions, simple molecules are joined to form a larger, more complex molecule.
- Anabolic reactions need a net input of energy to proceed. They are called endergonic reactions.

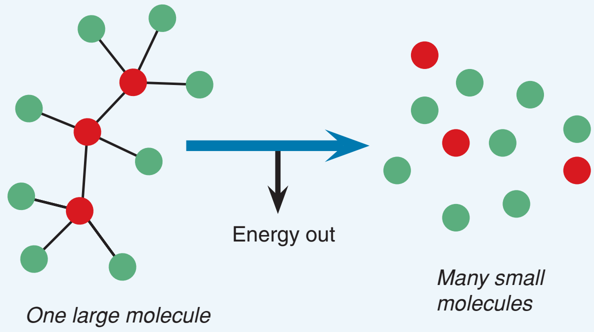


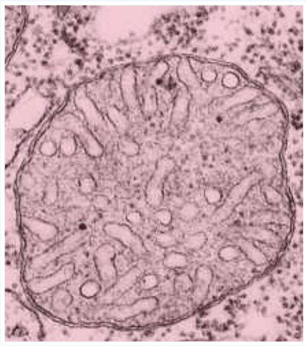


Photosynthesis is an example of an anabolic reaction pathway (many reactions are involved). Plants carry out photosynthesis in organelles called chloroplasts (left). Photosynthesis is an anabolic process because it converts carbon dioxide and water into glucose. Energy from the sun is required to drive photosynthesis.

Catabolic reactions

- **Catabolic reactions** are reactions that break down large molecules into smaller components.
- Catabolic reactions involve a net release of energy. They are called exergonic reactions.
- Catabolic reactions are the opposite of anabolic reactions.
- The energy released from catabolic reactions can be used to drive other metabolic processes.





Cellular respiration is an example of a catabolic reaction pathway. Glucose is broken down in a series of reactions to release carbon dioxide, water, and ATP (energy). The energy in ATP is used to fuel other activities in the cell. Most of the reactions of cellular respiration take place in the mitochondria (left).

1. What is an anabolic reaction? ______________________

____

2. (a) What is a catabolic reaction? ______________________

____

(b) Why are catabolic reactions considered to be the opposite to anabolic reactions? ______________________

____

____

3. Acidosis is a drop of blood pH to below 7.35 (normal blood pH is 7.35-7.45), which can be caused by kidney malfunction, alcohol intoxication, or starvation. Explain how acidosis might affect enzyme functioning and metabolism:

____

____

____

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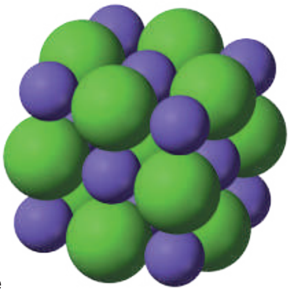
128 Salt Tolerance in Plants

Key Idea: Different species have differing tolerances to abiotic factors. Levels outside an organism's tolerance limits can reduce its chances of survival. Salt tolerance in plant species can be measured experimentally.

Tolerance limit is the ability to live within a certain range of abiotic factors (such as temperature or rainfall). For plants, salt tolerance is important because soil salinity affects plant growth and productivity. Above certain soil salinities, plants will not germinate or grow. In many regions of Australia, soil salinity is increasing (salinisation) lowering productivity. Human activities, such as removal of natural vegetation and poor irrigation management, contribute to salinisation.



Sodium chloride

Sodium chloride (NaCl) is an important contributor to soil salinisation. Increased soil salt concentrations have several negative effects on plants:

- High salt increases osmotic stress and decreases the ability of a plant to take up water.
- Large uptakes of Na^+ and Cl^- have a negative effect on growth by impairing metabolic processes and decreasing photosynthetic efficiency.

Plants can cope with NaCl to varying degrees. Some excrete excess salt onto their leaves (e.g. mangroves and salt grass) and other compartmentalise the salts (often in vacuoles).

The aim

Determine how temperature and salt levels influence the growth of salt grass (*Distichlis spicata*).

Salt grass (*Distichlis spicata*)

Matt Lavin CC 2.0

Salt grass (*Distichlis spicata*) is a native American plant found in a number of habitats including coastlines, desert scrub and marshes. It is very salt tolerant and capable of growing in very salty soils. Excess salt is excreted from its tissues onto the leaf surfaces.

The method

- Salt grass seeds were germinated in quartz sand and transplanted into their solutions of salt water when the fourth leaf appeared.
- The salt water concentrations were prepared by diluting sea water to obtain the following concentrations: 306, 612, 1834, and 2448 ppm.
- A nutrient enrichment solution was added to each sea water solution after dilution. The pH was adjusted to 5.7-6.0.
- Samples were prepared in duplicate.
- A control was grown in nutrient solution only.
- The plants were raised in greenhouses at either 12.7°C or 21.1°C.
- Material was harvested (as two cuttings) dried and weighed. The data are presented in the table below.

The results

Table 1: Effect of salt water concentration and temperature on salt grass growth

Concentration of sea water (ppm)	Weight of dry matter Average of 2 cultures (first cutting) (g)		Weight of dry matter Average of 2 cultures (second cutting) (g)		Total weight of dry matter (first cutting + second cutting) (g)	
	12.7°C	21.1°C	12.7°C	21.1°C	12.7°C	21.1°C
0 ppm + complete nutrient solution	47.0	21.2	49.0	25.3	96.0	46.5
306 ppm + dilute nutrient solution	14.4	8.3	21.2	12.5		
612 ppm + dilute nutrient solution	14.3	7.7	20.0	11.1		
1834 ppm + dilute nutrient solution	12.7	7.7	13.1	9.5		
2448 ppm + dilute nutrient solution	11.3	3.4	10.5	3.6		

Data: Ahi and Powers (1938) Salt tolerance of plants at various temperatures. Plant Physiol. 13 : 767-789.

1. Complete the table above by calculating the total weight of dry matter for each temperature and salt concentration. The first one has been done for you:

2. (a) Plot the total weight of dry matter at each temperature as a line graph on the grid (following page):

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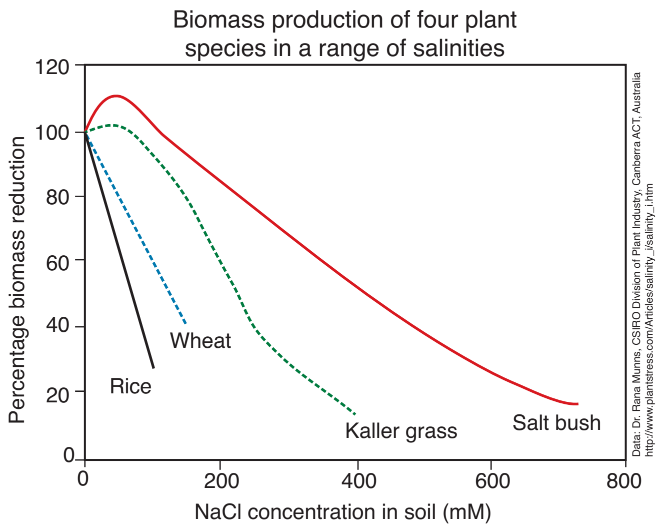
(b) Describe how salt water concentration and temperature affect salt grass growth: ______________________________

3. How does salt grass remove excess salts and suggest how might this help it to survive in saline conditions? __________

4. Wheat and rice are important food crops. The graph on the right shows their salt tolerance compared to two salt adapted species. Based on the data for salt grass, and assuming that salinisation will continue to be a problem, how might increasing soil salinity affect productivity of these important food crops in Australia?



5. How could the development of salt tolerant plants (e.g. through genetic modification) benefit Australian farmers?

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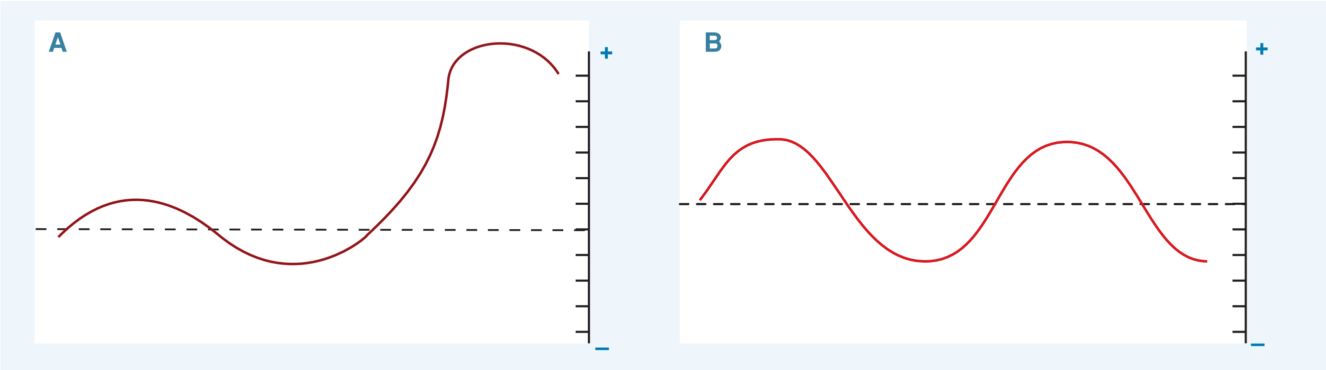
129 KEY TERMS AND IDEAS: Did You Get It?

1. Test your knowledge about feedback mechanisms by studying the two graphs below and answering the questions about them. In your answers, use biological terms appropriately to show your understanding.



Type of feedback mechanism: ______________________

Mode of action: ______________________

Biological examples of this mechanism: ______________________

Type of feedback mechanism: ______________________

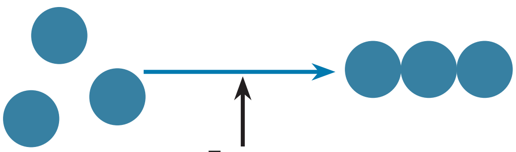
Mode of action: ______________________

Biological examples of this mechanism: ______________________

2. (a) What type of metabolic reaction is taking place in the diagram right?

____

(b) What is occurring during this reaction? ______________________



(c) Give an example of this type of metabolic reaction: ______________________

3. Test your vocabulary by matching each term to its definition, as identified by its preceding letter code.

chemoreceptor ....

homeostasis ....

mechanoreceptor ....

negative feedback ....

nociceptor ....

positive feedback ....

receptor ....

stimulus ....

A A mechanism in which the output of a system acts to oppose changes to the input of the system. The net effect is to stabilise the system and dampen fluctuations.

B Any change in the environment capable of generating a response in an organism.

C A receptor stimulated by noxious, potentially damaging stimuli.

D A receptor that detects the presence of chemicals.

E A destabilising mechanism in which the output of the system causes an escalation in the initial response.

F A receptor that detects distortion as caused by touch, pressure, vibration, or tension.

G A sensory structure that responds to a stimulus in the internal or external environment of an organism.

H Regulation of the internal environment to maintain a stable, constant condition.

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UNIT 2
Topic 1

Neural Homeostatic Control Pathways

Key terms

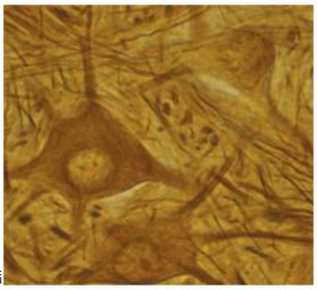
acetylcholine
action potential
depolarisation
hyperpolarisation
inhibition
motor neurone
myelin
nerve impulse
neurone
node of Ranvier
refractory period
resting potential
sensory neurone
summation
synapse
synaptic integration
threshold

Activity number

Structure and function of neurones

Key skills and knowledge

- ☐ 1 Recall the role of the nervous system in receiving stimuli through sensory receptors and responding to those stimuli through effectors. Identify pathways for neural coordination in a mammal, e.g. human, including reference to the role of the central nervous system in integrating the information and coordinating appropriate responses to stimuli. **130**
- ☐ 2 Identify the cells that transmit nerve impulses from sensory receptors to the central nervous system and from the central nervous system to effectors. **130**
- ☐ 3 Distinguish between sensory and motor neurones in terms of their structure and function. Include reference to dendrites, soma (cell body), axon, myelin sheath, nodes of Ranvier, axon terminal, and synapse. **131**
- ☐ 4 Describe the role of reflexes in providing rapid responses to stimuli. Giving examples, distinguish between monosynaptic and polysynaptic reflex arcs. **132**
- ☐ 5 **PRAC** Investigate simple reflex arcs, e.g. stretch reflexes, cutaneous reflexes, and/or cranial reflexes such as the pupillary reflex. **132**



Transmission of nerve impulses

Key skills and knowledge

- ☐ 6 Describe the generation and transmission of nerve impulses in mammals. Include reference to how the resting potential is established and maintained and how the action potential is generated and transmitted by saltatory conduction. Include reference to the significance of threshold stimulation and the importance of the refractory period and synaptic transmission in producing discrete impulses that travel in one direction. **133**
- ☐ 7 Describe the structure of a chemical synapse (e.g. a cholinergic synapse). Identify pre- and post-synaptic neurones, vesicles containing neurotransmitter (e.g. acetylcholine), and the synaptic cleft. **134**
- ☐ 8 Describe impulse transmission across a synapse (e.g. a cholinergic synapse) to include the role of calcium, diffusion of the neurotransmitter (e.g. acetylcholine), and generation of an action potential in the post-synaptic cell. Recognise that the effect of the neurotransmitter depends on the neurotransmitter involved, its position in the nervous system, and the properties of the post-synaptic cell. **134**
- ☐ 9 Explain synaptic integration and the role of synapses in summation and control of nervous system responses. **135**
- ☐ 10 Recognise that synaptic transmission can be affected by drugs and poisons (e.g. snake venom). The drug or poison may either increase the neurotransmitter's usual effect (agonist) or decrease the neurotransmitter's usual effect (antagonist). **136**
- ☐ 11 **SHE** Describe how antivenoms can be produced using synthetic DNA. Explain how this could replace conventional methods of antivenom production.

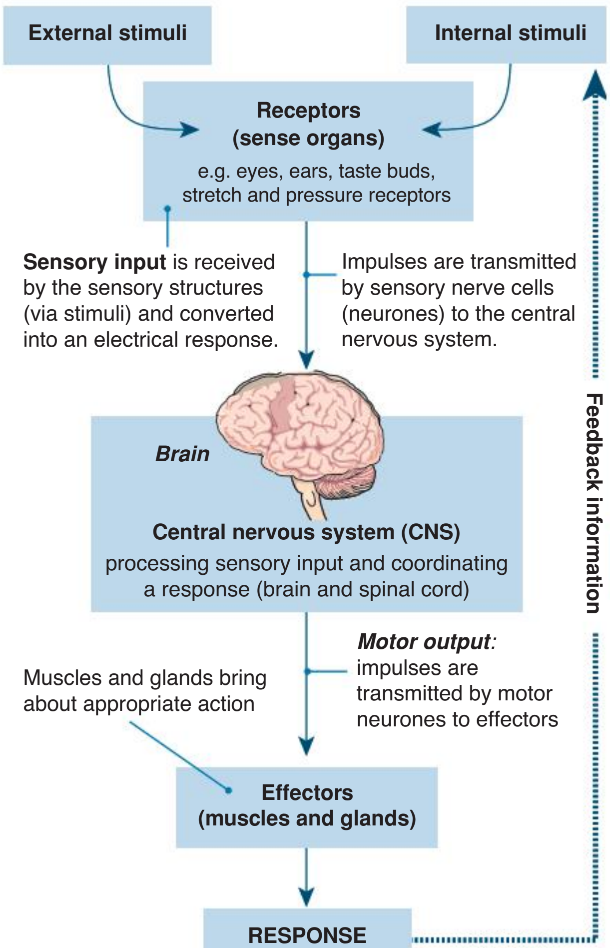
130 Nervous Regulation in Vertebrates

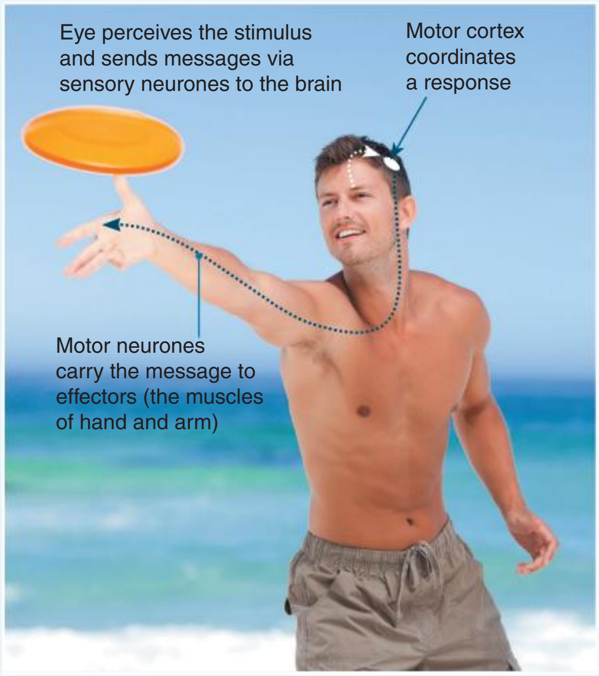
Key Idea: The nervous and endocrine systems work together to maintain homeostasis. Neurones of the nervous system transmit information as nerve impulses to the central nervous system, which coordinates appropriate responses to stimuli.

In humans, the nervous and endocrine (hormonal) systems work together to regulate the internal environment and maintain homeostasis in a fluctuating environment. The nervous system includes cells called **neurones** (nerve cells) which are specialised to transmit information in the form of electrochemical impulses (action potentials). The nervous system is a signalling network with branches carrying information directly to and from specific target tissues. Impulses can be transmitted over considerable distances and the response is very precise and rapid.

Coordination by the nervous system

The vertebrate nervous system consists of the central nervous system (brain and spinal cord), and the nerves and receptors outside it (peripheral nervous system). Sensory input to receptors comes via stimuli. Information about the effect of a response is provided by feedback mechanisms so that the system can be readjusted. The basic organisation of the nervous system can be simplified into a few key components: the sensory receptors, a central nervous system processing point, and the effectors, which bring about the response.





In the example above, the frisbee's approach is perceived by the eye. The motor cortex of the brain integrates the sensory message. Coordination of hand and body orientation is brought about through motor neurones to the muscles.

Comparison of nervous and hormonal control

	Nervous control	Hormonal control
Communication	Impulses across synapses	Hormones in the blood
Speed	Very rapid (within a few milliseconds)	Relatively slow (over minutes, hours, or longer)
Duration	Short term and reversible	Longer lasting effects
Target pathway	Specific (through nerves) to specific cells	Hormones broadcast to target cells everywhere
Action	Causes glands to secrete or muscles to contract	Causes changes in metabolic activity

1. Identify the three basic components of a nervous system and describe their role:

(a) ______________________________

(b) ______________________________

(c) ______________________________

2. Comment on the significance of the differences between the speed and duration of nervous and hormonal controls:

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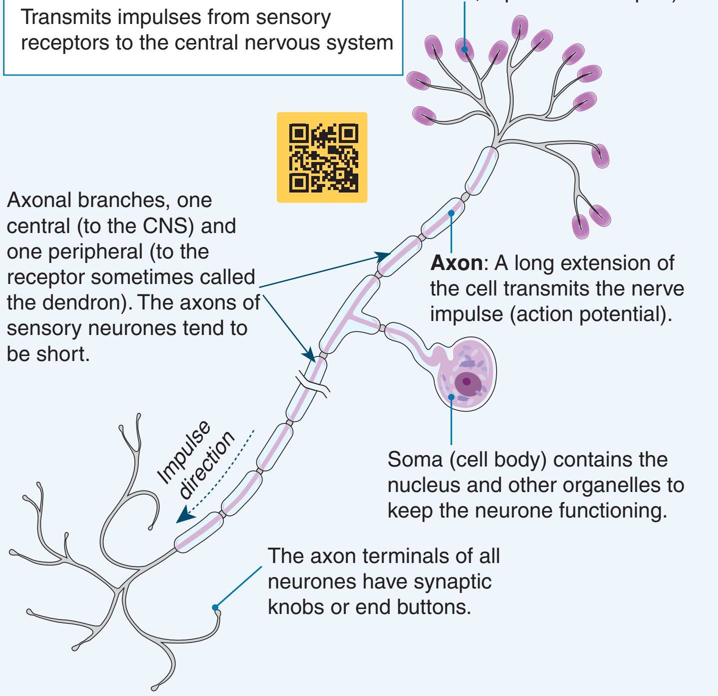
131 Neurones

Key Idea: Neurones conduct electrical impulses from sensory receptors along axons to other neurones or to effector cells.

Neurones (nerve cells) are electrically excitable cells that transmit nerve impulses. Neurones have a recognisable structure with a cell body (soma) and long processes (dendrites and axons). Most neurones in the peripheral nervous system (nerves outside the brain and spinal cord) are also supported by a fatty insulating sheath of myelin, which increases the speed of impulse conduction. Information, in the form of electrochemical impulses, is transmitted along neurones from receptors to a coordination centre and then to effectors. The speed of impulse conduction depends primarily on the axon diameter and whether or not the axon is myelinated.

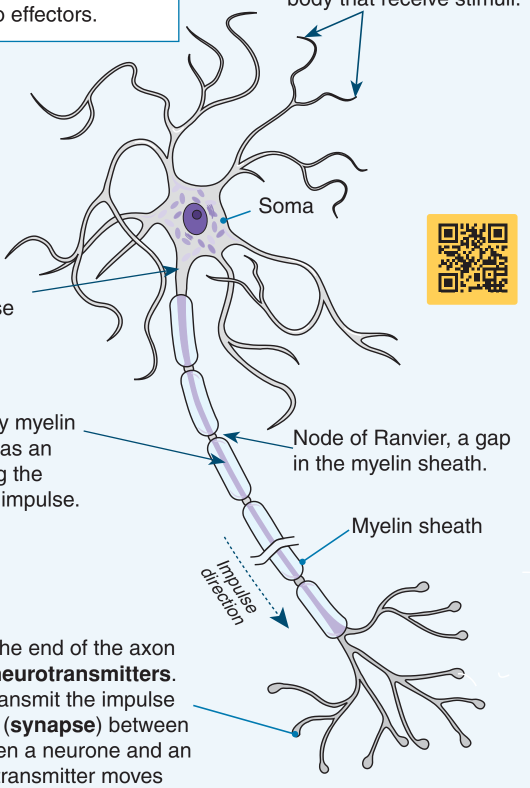
Sensory neurone

Transmits impulses from sensory receptors to the central nervous system



Motor neurone

Transmits impulses from the central nervous system to effectors.



1. Describe the basic structure of a neurone:

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2. (a) Describe the structural differences between a motor and a sensory neurone:

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(b) Describe a functional difference between a motor and a sensory neurone:

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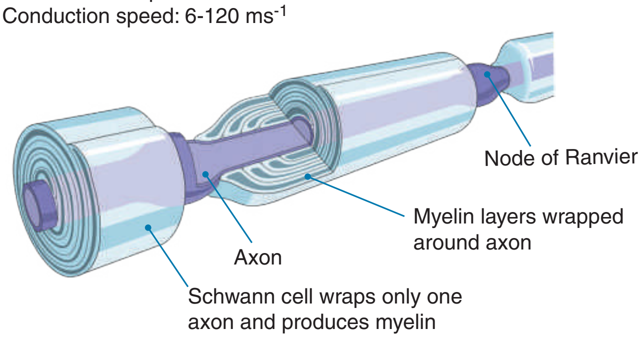
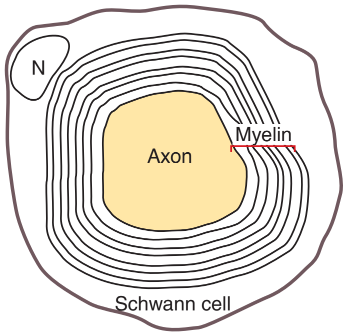
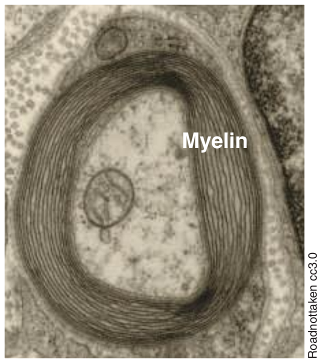
Myelinated neurones

Where conduction speed is important, the axons of neurones are sheathed within a lipid-rich substance called **myelin**. Outside the CNS, in the peripheral nervous system, myelin is produced by specialised cells called Schwann cells. At intervals along myelinated axons, there are gaps between neighboring Schwann cells and their sheaths called **nodes of Ranvier**. Myelin acts as an insulator, increasing the speed at which nerve impulses travel because it forces the impulse to "jump" from one uninsulated region to the next.

Diameter: 1-25 μm
Conduction speed: 6-120 ms^{-1}





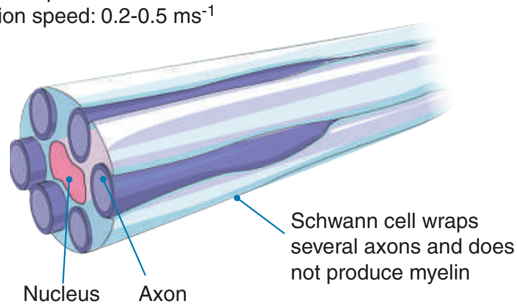


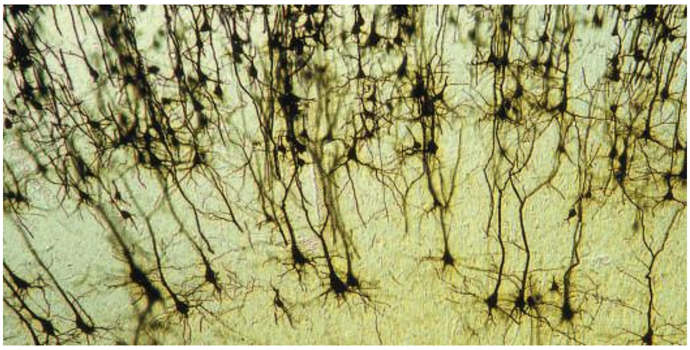
Drawing (above left) and TEM cross section (above right) through a myelinated axon. N = nucleus of Schwann cell.

Non-myelinated neurones

Non-myelinated axons are more common in the CNS where the distances travelled are less than in the peripheral nervous system. Here, the axons are protected by Schwann cells, but there is no myelin produced. Impulses travel more slowly because the nerve impulse is propagated along the entire axon membrane, rather than jumping from node to node as in myelinated neurones.

Diameter: <1 μm
Conduction speed: 0.2-0.5 ms^{-1}





Unmyelinated pyramidal neurones in the cerebral cortex of the brain.

3. (a) What do neurones do? ______________________________

   (b) How does this differ from supporting cells (e.g. Schwann cells)? ______________________________

4. What is the purpose of the synaptic knobs at axon terminals? ______________________________

5. (a) What is the function of myelination in neurones? ______________________________

   (b) What cell type produces the myelin sheath in the peripheral nervous system? ______________________________

   (c) Explain how an action potential travels in a myelinated neurone: ______________________________

   (d) How does this differ from its travel in a non-myelinated neurone? ______________________________

   (e) Why do motor neurones outside the CNS tend to be myelinated? ______________________________

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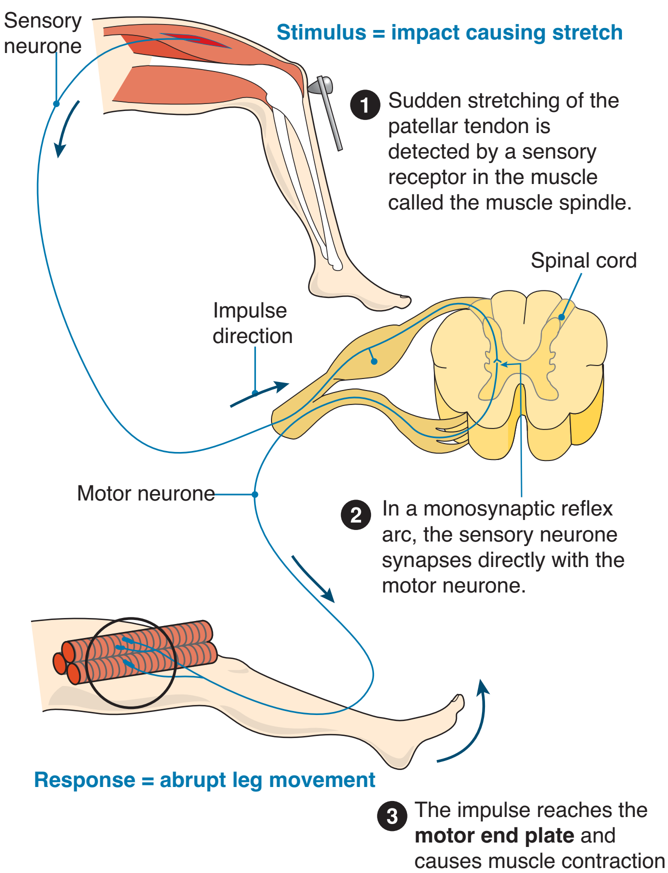
132 Reflexes

Key Idea: A reflex is an involuntary response to a stimulus.

A **reflex** is an automatic response to a stimulus involving a small number of neurones and a central nervous system (CNS) processing point (usually the spinal cord, but sometimes the brain stem). This type of circuit is called a **reflex arc**. Reflexes permit rapid responses to stimuli. They are classified according to the number of CNS synapses involved. **Monosynaptic reflexes** involve only one CNS synapse (e.g. knee jerk reflex), whereas **polysynaptic reflexes** involve two or more (e.g. pain withdrawal reflex). Both are spinal reflexes. The pupil reflex (opening and closure of the pupil) is an example of a cranial reflex.

Knee-jerk reflex: A monosynaptic reflex arc



The patella (knee jerk) (left) reflex is a simple deep tendon reflex used to test the function of the femoral nerve and spinal cord segments L2-L4. It helps to maintain posture and balance when walking.

The pupillary light reflex refers to the rapid expansion or contraction of the pupils in response to the intensity of light falling on the retina. It is a polysynaptic cranial reflex and can be used to test for brain death.

Normal newborns exhibit a number of primitive reflexes in response to particular stimuli. These reflexes disappear within a few months of birth as the child develops. Primitive reflexes include the grasp reflex (above left) and the startle or Moro reflex (above right) in which a sudden noise will cause the infant to throw out its arms, extend the legs and head, and cry. The rooting and sucking reflexes are further examples of primitive reflexes.

1. Reflexes do not require conscious thought to occur. How does this provide a survival advantage? ____________________

2. (a) Describe the difference between a monosynaptic and a polysynaptic reflex arc: ____________________

   (b) Which would produce the most rapid response, given similar length sensory and motor pathways? Explain: ____________________

3. What might be the survival advantage of primitive reflexes in newborns? ____________________

4. Using the resource provided via BIOZONE's weblinks page, work in pairs to investigate simple reflex arcs.

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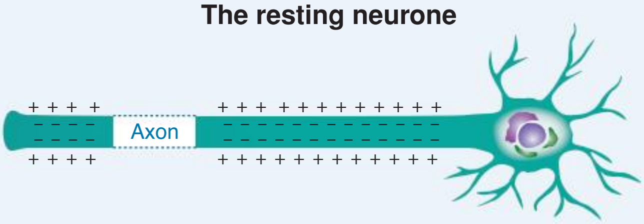
133 Transmission of Nerve Impulses

Key Idea: A nerve impulse occurs in response to a stimulus and involves the transmission of a membrane depolarisation along the axon of a neurone.

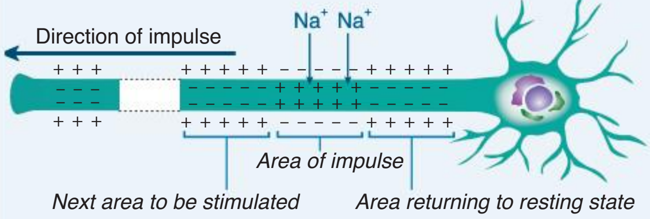
The plasma membrane of cells, including neurones, contain **sodium-potassium ion pumps** which actively pump sodium ions (Na^+) out of the cell and potassium ions (K^+) into the cell. The action of these ion pumps in neurones creates a separation of charge (a potential difference or voltage) either side of the membrane and makes the cells **electrically excitable**. It is this property that enables neurones to transmit electrical impulses. The **resting state** of a neurone, with a net negative charge inside, is maintained by the sodium-potassium pumps, which actively move two K^+ into the neurone for every three Na^+ moved out (below left). When a nerve is stimulated, a brief increase in membrane permeability to Na^+ temporarily reverses the membrane polarity (a **depolarisation**). After the nerve impulse passes, the sodium-potassium pump restores the resting potential.

The resting neurone

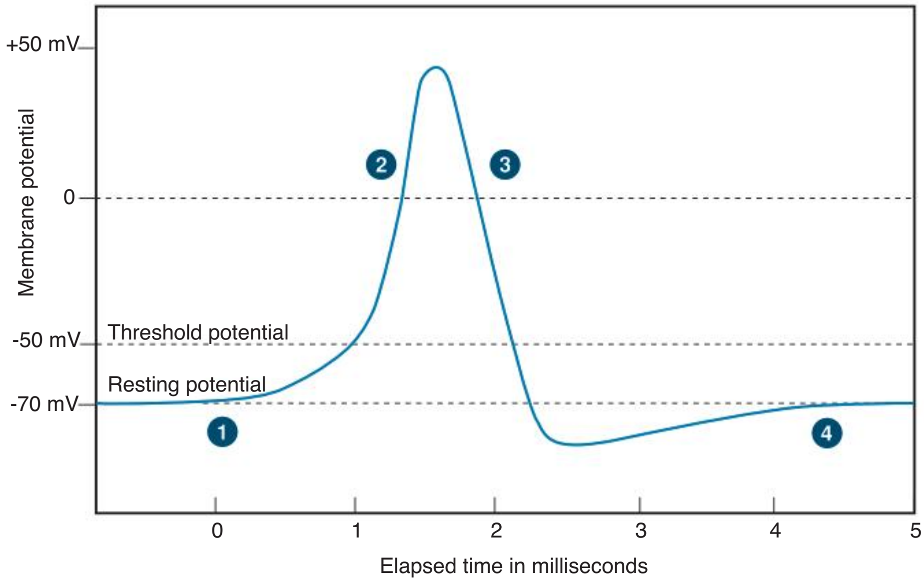


When a neurone is not transmitting an impulse, the inside of the cell is negatively charged relative to the outside and the cell is said to be electrically polarized. The potential difference (voltage) across the membrane is called the **resting potential**. For most nerve cells this is about -70 mV. Nerve transmission is possible because this membrane potential exists.

The nerve impulse



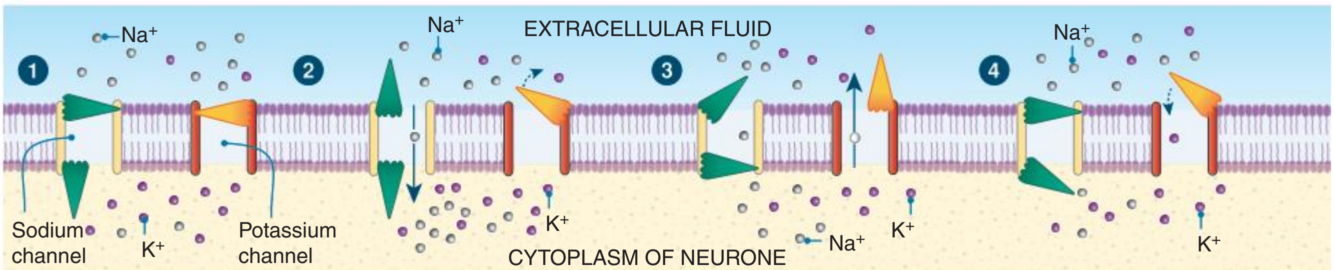
When a neurone is stimulated, the distribution of charges on each side of the membrane briefly reverses. This process of **depolarisation** causes a burst of electrical activity to pass along the axon of the neurone as an **action potential**. As the charge reversal reaches one region, local currents depolarise the next region and the impulse spreads along the axon.



The depolarisation in an axon can be shown as a change in membrane potential (in millivolts). A stimulus must be strong enough to reach the **threshold potential** before an action potential is generated. This is the voltage at which the depolarisation of the membrane becomes unstoppable.

The action potential is **all or nothing** in its generation and because of this, impulses (once generated) always reach threshold and move along the axon without weakening. The resting potential is restored by the movement of potassium ions (K^+) out of the cell. During this **refractory period**, the nerve cannot respond, so nerve impulses are discrete.

Voltage-gated ion channels and the course of an action potential



Resting state:
Voltage activated Na^+ and K^+ channels are closed. Negative interior is maintained by the Na^+/K^+ pump.

Depolarisation:
Voltage activated Na^+ channels open and there is a rapid influx of Na^+ ions. The interior of the neurone becomes positive relative to the outside.

Repolarisation:
Voltage activated Na^+ channels close and the K^+ channels open; K^+ moves out of the cell, restoring the negative charge to the cell interior.

Returning to resting state:
Voltage activated Na^+ and K^+ channels close and the Na^+/K^+ pump restores the original balance of ions, returning the neurone to its resting state ($3Na^+$ out for $2K^+$ in).

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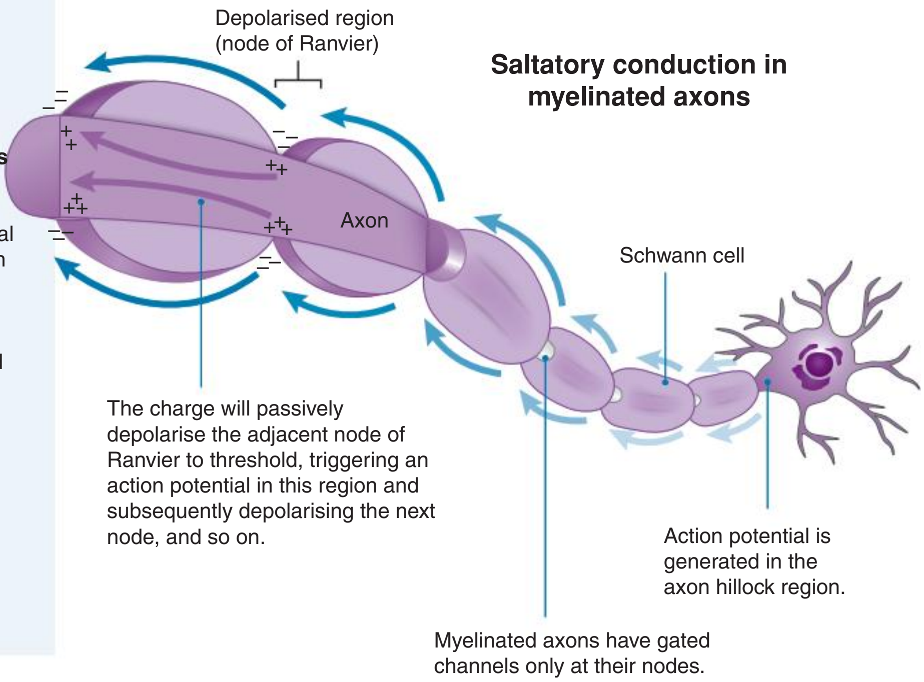
Axon myelination is a feature of vertebrate nervous systems and it enables them to achieve very rapid speeds of nerve conduction.

In a myelinated neurone, **action potentials are generated only at the nodes**, which is where the voltage gated channels occur. The axon is insulated so the action potential at one node is sufficient to trigger an action potential in the next node and the impulse 'jumps' along the axon (called **saltatory conduction**). This contrasts with a non-myelinated neurone in which voltage-gated channels occur along the entire length of the axon.

As well as increasing the speed of conduction, the myelin sheath reduces energy expenditure because the area over which depolarisation occurs is less (and therefore also the number of sodium and potassium ions that need to be pumped to restore the resting potential).



1. What is an action potential? ______________________________

____

2. Describe the movement of voltage-gated channels and ions associated with:

   (a) Depolarisation of the neurone: ______________________________

   (b) Repolarisation of the neurone: ______________________________

3. Summarise the sequence of events in a neurone when it receives a stimulus sufficient to reach threshold:

   (i): ______________________________

   ____

   (ii): ______________________________

   ____

   (iii): ______________________________

   ____

   (iv): ______________________________

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4. (a) Explain why the nerve impulse in a myelinated neurone jumps along the axon from node to node:

   ____

   ____

   (b) How does myelination reduce the energetic costs of impulse conduction? ______________________________

   ____

   ____

5. How is the resting potential restored in a neurone after an action potential has passed? ______________________________

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6. Explain how the refractory period influences the direction in which an impulse will travel: ______________________________

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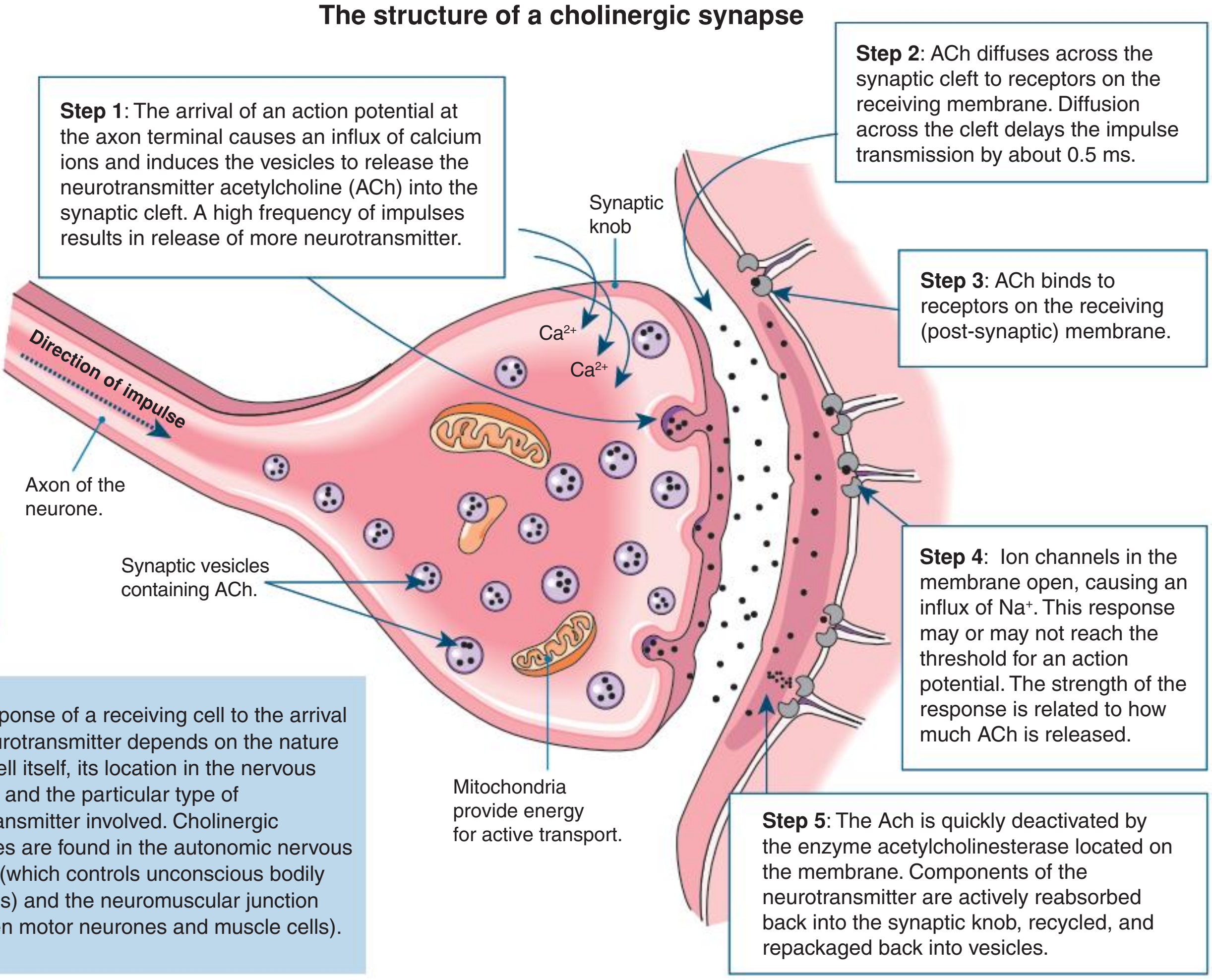
134 Chemical Synapses

Key Idea: Synapses are junctions between neurones, or between neurones and receptor or effector cells. Nerve impulses are transmitted across synapses.

Action potentials are transmitted across junctions called synapses. Almost all synapses in vertebrates are chemical synapses, which involve the diffusion of a signal molecule or neurotransmitter from one cell to another. Chemical synapses can occur between two neurones, between a receptor cell and a neurone, or between a neurone and an effector (e.g. muscle fibre or gland cell). The synapse consists of the axon terminal (synaptic knob), a gap called the synaptic cleft, and the membrane of the post-synaptic (receiving) cell. Arrival of an action potential at the axon terminal causes release of the neurotransmitter, which diffuses across the cleft and produces an electrical response in the post-synaptic cell (an example of **signal transduction**). Cholinergic synapses are named for the neurotransmitter they release, acetylcholine (ACh). In the example pictured below, ACh results in depolarisation (excitation) of the post-synaptic neurone. Unlike electrical synapses, in which transmission can occur in either direction, transmission at chemical synapses is always in one direction (unidirectional).

The structure of a cholinergic synapse



The response of a receiving cell to the arrival of a neurotransmitter depends on the nature of the cell itself, its location in the nervous system, and the particular type of neurotransmitter involved. Cholinergic synapses are found in the autonomic nervous system (which controls unconscious bodily functions) and the neuromuscular junction (between motor neurones and muscle cells).

1. (a) What is a synapse? ______________________________

   (b) What defines a cholinergic synapse? ______________________________

2. What causes the release of neurotransmitter into the synaptic cleft? ______________________________

3. Why is there a brief delay in impulse transmission across the synapse? ______________________________

4. What determines the strength of the response in the receiving cell? ______________________________

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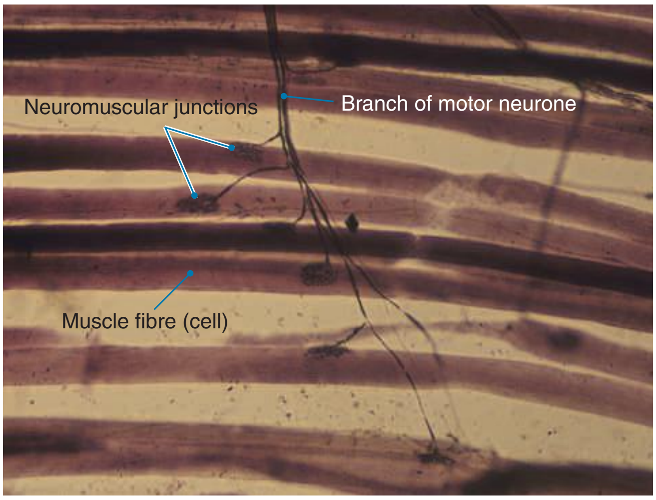
The neuromuscular junction

The neuromuscular junction is a specialised cholinergic synapse between a motor neurone and a muscle fibre. Functionally, they operate in the same way as the excitatory cholinergic synapse pictured opposite.

- Arrival of an action potential at the neuromuscular junction results in depolarisation of the muscle fibre membrane (the sarcolemma) and this results in contraction of the muscle fibre.
- For a muscle fibre to contract, it must receive a threshold stimulus in the form of an action potential. Action potentials are carried by motor neurones from the central nervous system to the muscle fibres they supply. The arrival of an action potential at the neuromuscular junction results in release of the neurotransmitter acetylcholine and contraction of the fibre.
- The response of a single muscle fibre is **all-or-none**, meaning it contracts maximally or not at all. This differs from the graded response that can occur with transmission between neurones.



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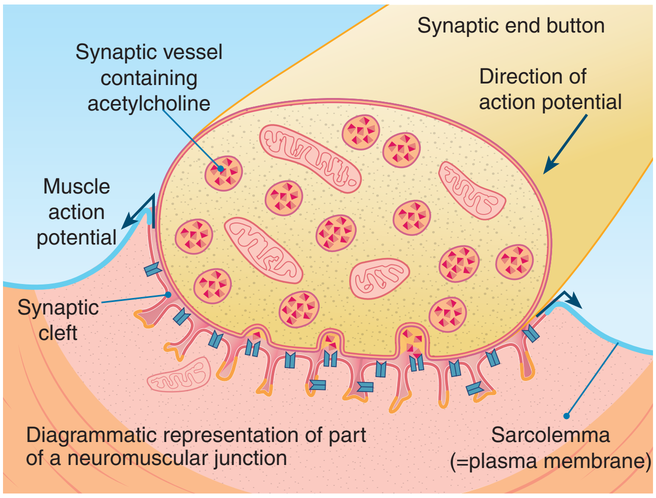
Axon terminals of a motor neurone supplying a muscle. Axon branches end on the sarcolemma (plasma membrane) of a muscle fibre at regions called neuromuscular junctions. Each fibre receives a branch of an axon, but one axon may supply many muscle fibres. A motor neurone and all the fibres it innervates is called a motor unit.



When an action potential arrives at the neuromuscular junction on a muscle cell (fibre), it causes release of acetylcholine, which diffuses across the synaptic cleft to stimulate an action potential in the sarcolemma. The action potential travels throughout the muscle fibre causing muscle contraction.

5. What factors determine the response of the post-synaptic cell? ______________________

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6. (a) How is the neurotransmitter is deactivated? ______________________

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(b) Why do you think it is important for the neurotransmitter to be deactivated soon after its release? ______________________

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(c) Why is transmission at chemical synapses unidirectional and what is the significance of this? ______________________

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7. (a) In what way is the neuromuscular junction (above) similar to the cholinergic synapse described opposite: ______________________

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(b) In what ways are these two synaptic junctions different? ______________________

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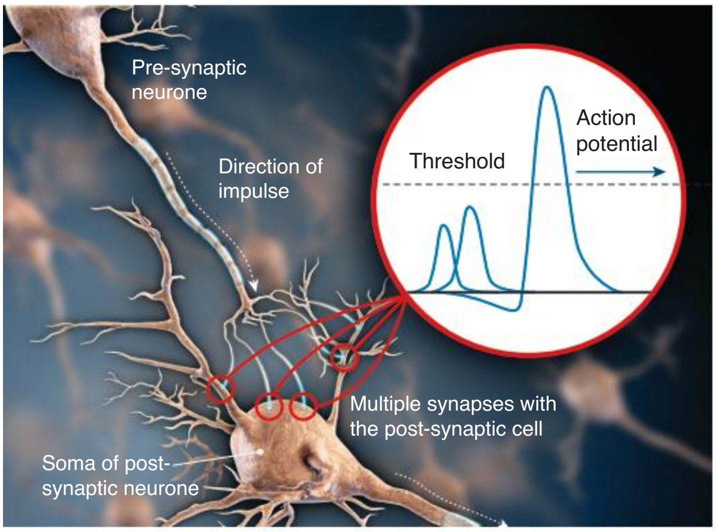
135 Integration at Synapses

Key Idea: Synapses play a pivotal role in the ability of the nervous system to respond appropriately to stimulation and to adapt to change by integrating all inputs.

The nature of synaptic transmission in the nervous system allows the **integration** (interpretation and coordination) of inputs from many sources. These inputs can be excitatory (causing depolarisation) or inhibitory (making an action potential less likely). It is the sum of all excitatory and inhibitory inputs that leads to the final response in a post-synaptic cell. Synaptic integration is behind all the various responses we have to stimuli. It is also the most probable mechanism by which learning and memory are achieved.

Summation at synapses

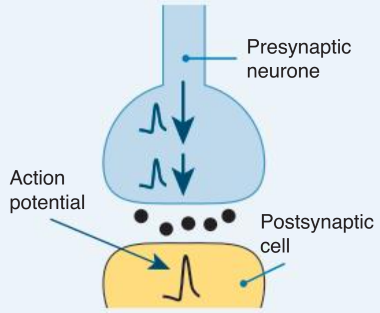
Graded postsynaptic responses may sum to produce an action potential.



Impulse transmission across chemical synapses has several advantages, despite the delay caused by neurotransmitter diffusion. Chemical synapses transmit impulses in one direction to a precise location and, because they rely on a limited supply of neurotransmitter, they are subject to fatigue (inability to respond to repeated stimulation). This protects the system against overstimulation.

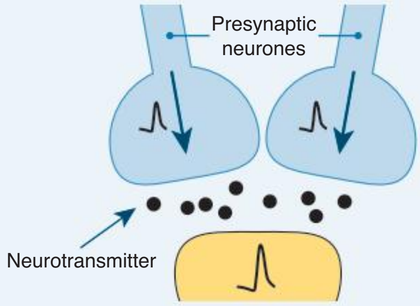
Synapses allow inputs from many sources to be **integrated**. The response of a post-synaptic cell is often not strong enough on its own to generate an action potential. However, because the strength of the response is related to the amount of neurotransmitter released, subthreshold responses can sum together to produce a response in the post-synaptic cell. This additive effect is called **summation**. Summation can be temporal or spatial (right).

1 Temporal summation



Several impulses may arrive at the synapse in quick succession from a single axon. The individual responses are so close in time that they sum to reach threshold and produce an action potential in the post-synaptic neurone.

2 Spatial summation



Impulses from spatially separated axon terminals may arrive simultaneously at different regions of the same post-synaptic neurone. The responses from the different places sum to produce an action potential.

1. Explain the purpose of nervous system integration: ______________________

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2. Describe two advantages of chemical synapses:

(a) ______________________

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(b) ______________________

____

3. (a) Explain what is meant by summation: ______________________

____

(b) In simple terms, distinguish between temporal and spatial summation: ______________________

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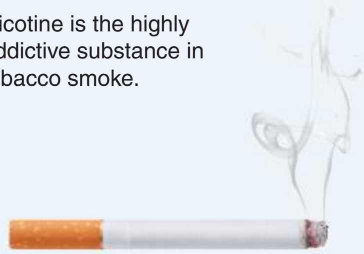
136 Drugs at Synapses

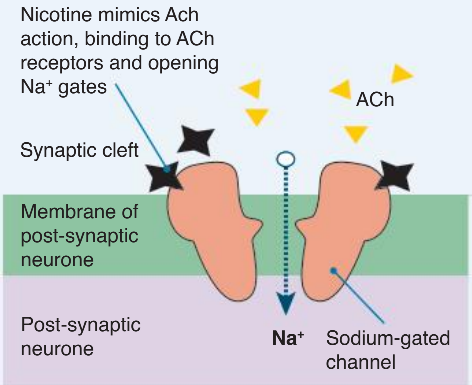
Key Idea: Drugs may increase or decrease the effect of neurotransmitters at synapses.

Drugs may act at synapses either mimicking or blocking the usual effect of a neurotransmitter (whether it be excitatory or inhibitory). Drugs that increase the usual effect of a neurotransmitter are called **agonists** while those that decrease their effect are called **antagonists**. Many recreational and therapeutic drugs work through their action at synapses, controlling the response of the receiving cell to incoming action potentials.

Nicotine

Nicotine is the highly addictive substance in tobacco smoke.

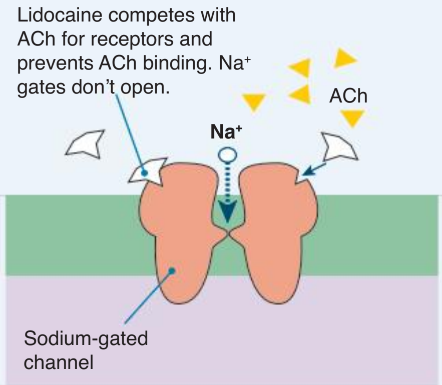




Effect: Agonistic
Result: Action potential generation
Nicotine acts as an agonist at nicotinic synapses (autonomic ganglia and the motor end plate). It binds to and activates ACh receptors on the postsynaptic membrane (e.g. of a muscle cell). This opens sodium gates, leading to a sodium influx and membrane depolarisation.

Lidocaine

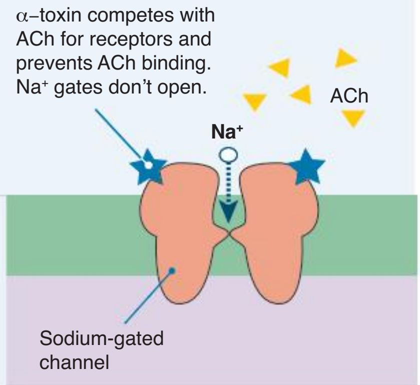
Lidocaine is a quick-acting local anaesthetic used to block pain during minor surgery or dental work.



Effect: Antagonistic
Result: Sensory inhibition
Lidocaine binds to the ACh receptors on sensory neurons and prevents ACh binding. No depolarisation occurs, so no action potential is generated on the post-synaptic neuron. Pain signals are not generated.

Cobra venom

Cobra venom contains many neurotoxins (chemicals affecting the nervous tissue). Some bind tightly and irreversibly to ACh receptors.



Effect: Antagonistic
Result: Muscular paralysis
Toxins in cobra venom bind to ACh receptors and prevent ACh binding to receptors on the plasma membrane of muscle cells. As a result, sodium channels remain closed and no action potentials are produced. They can cause muscular paralysis, respiratory failure, and death.

1. Explain the difference between an agonistic and antagonistic drug: ______________________________

2. Nicotine and cobra venom both bind to acetylcholine receptors. Explain why their effects are different: ______________________________

3. Explain why lidocaine is used as a local anaesthetic: ______________________________

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137 Snake Antivenom Production

Key Idea: Snake antivenom is used to neutralise snake venom. It can be made using traditional immunological techniques or modern techniques utilising synthetic DNA.

Snake venoms are some of nature's most deadly substances. The World Health Organisation has listed antivenom as one of the essential medicines of a basic health system. However producing antivenom is problematic. Snake antivenom is traditionally made by first "milking" the snake by getting it to bite down on the lip of a jar so that it produces venom, which can then be collected. Small (non-lethal) amounts of venom are then injected into horses over a period of several months. The horses produce antibodies to the venom in their blood. The blood is then collected and the antibodies refined from the blood plasma. This process is difficult, time consuming, and only produces a relatively small amount of antivenom. This leads to shortages of antivenom. To combat these problems, new techniques to create synthetic antivenoms are being developed.

Snake venom

Snake venom can be divided into three main types:

The coastal taipan's venom contains a potent neurotoxin

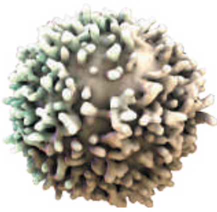
Cytotoxic venoms start digesting the prey as soon as it is bitten. The venom destroys cells, collapsing tissues (especially muscle tissue).

Haemotoxic venoms work in one of two ways. They either cause the blood to coagulate, causing death through widespread blood clotting, or they destroy blood vessels and causing death through internal bleeding.

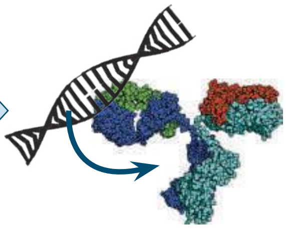
Neurotoxic venoms affect the nervous system, acting at synapses to cause paralysis and death by asphyxiation or heart failure. These are the fastest acting venoms.

Producing synthetic antivenom

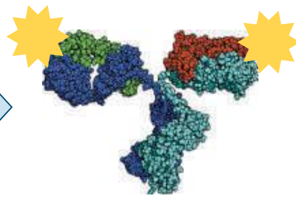
A non-lethal dose of snake venom is injected into a llama.



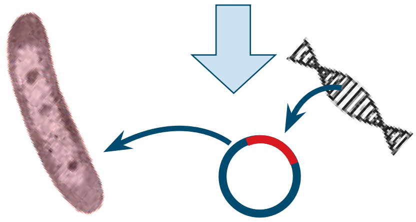
Antibody producing B cells are collected from the blood and the active genes are identified.



The genes are sequenced and the antibodies they encode synthesised.



The antibodies are mixed with snake venom. The molecules that bind most effectively are isolated.



The genes coding for these molecules are synthesised and spliced into the DNA of *E. coli* bacteria using genetic engineering techniques.

The bacteria are incubated and the antibody molecules they produce are refined.

The antibody molecules are used to make antivenoms.

1. Explain the difficulties with the traditional production of snake antivenom: ______________________________

____

____

____

2. Explain how producing synthetic antibodies allows a greater quantity of antivenom to be produced as well as a greater variety of antivenoms:

____

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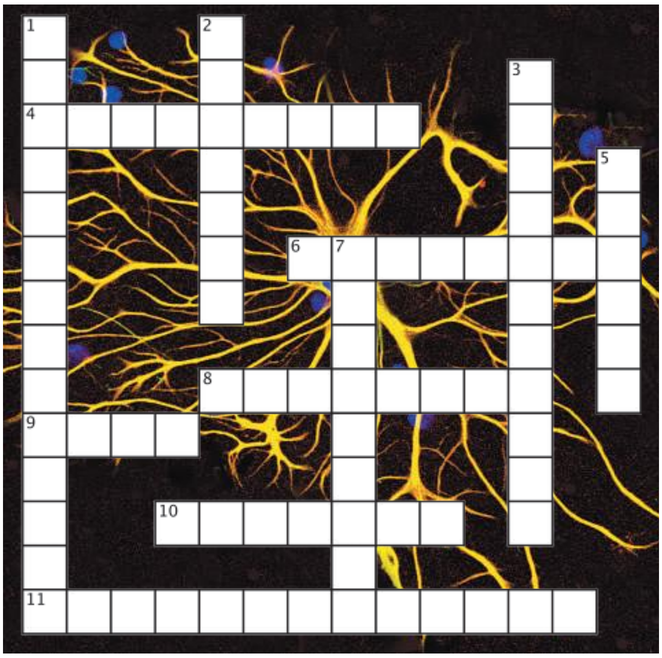
138 KEY TERMS AND IDEAS: Did You Get It?

1. Complete the crossword below:


GerryShaw CC 3.0

Across

4. A self propagating nerve impulse is called an action _ _ _ _ _ _ _ _ _ .
6. Extension of the nerve cell body specialised to receive stimuli.
8. A specialised cell that detects stimuli and responds by producing a nerve impulse.
9. Long extension of the nerve cell which transits the nerve impulse to another cell.
10. A cell specialised to transmit electrical impulses.
11. An organ system made up of a network of specialised cells or neurones, which coordinates responses and transmits signals between parts of the body (2 words).

Down

1. A temporary change in membrane potential caused by influx of sodium ions.
2. The gap between neighbouring neurones or between a neurone and an effector.
3. These synapses release acetylcholine.
5. This lipid-rich substance surrounds and insulates the axons of nerves in the peripheral nervous system.
7. Motor nerves carry impulses from the central nervous system to these.

2. (a) Label the components of this neurone (right) using the following word list: *cell body, axon, dendrites, node of Ranvier.*

(b) Is this neurone myelinated or unmyelinated?(delete one)

(c) Explain your answer: ______________________

____

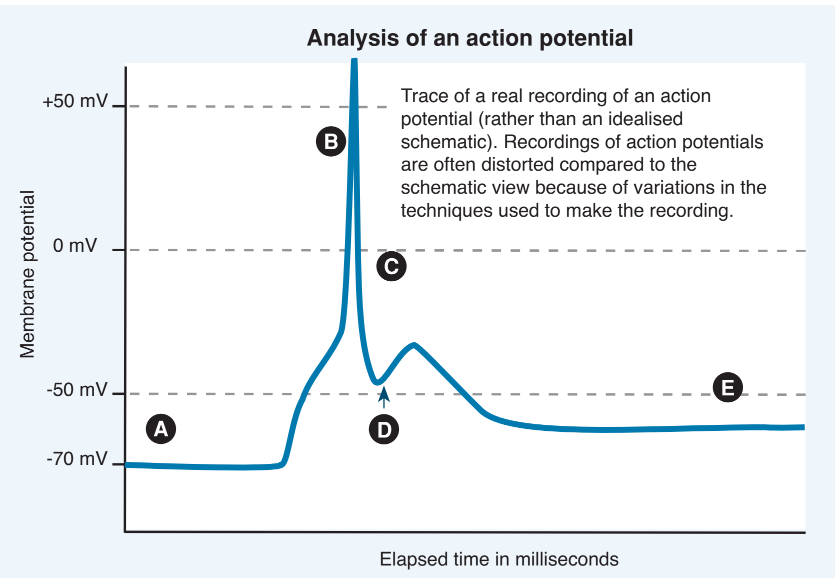
____

____

(d) In what form do electrical signals travel in this cell?

____

3. (a) The graph below shows a recording of the changes in membrane potential in an axon during transmission of an action potential. Match each stage (A-E) to the correct summary provided below.



☐ Membrane depolarisation (due to rapid Na^+ entry across the axon membrane.

☐ Hyperpolarisation (an overshoot caused by the delay in closing of the K^+ channels.

☐ Return to resting potential after the stimulus has passed.

☐ Repolarisation as the Na^+ channels close and slower K^+ channels begin to open.

☐ The membrane's resting potential.

(b) What is the resting potential of the axon? ______________________

(c) What is the maximum voltage reached by the action potential? ______________________

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UNIT 2
Topic 1

Hormonal Homeostatic Controls

Key terms

down regulation

extracellular receptor

first messenger

G-protein coupled receptor

hormone

hydrophilic signal

hydrophobic signal

intracellular receptor

neurotransmitter

pheromone

phosphorylation cascade

second messenger

signal molecule

signal transduction

target cell

transcription factor

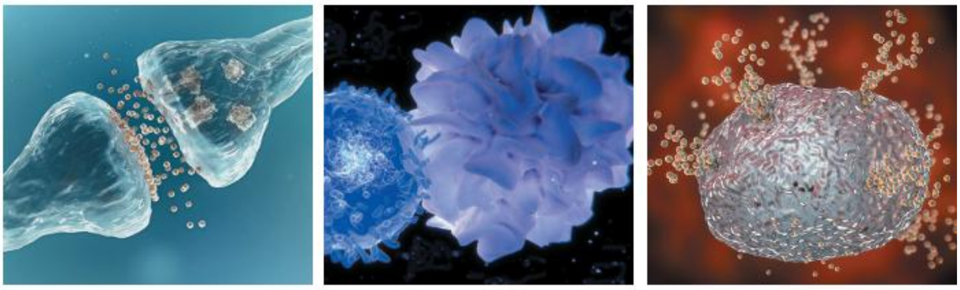
upregulation

Activity number

Hormones are signalling molecules

Key skills and knowledge

			Activity number
☐	1	Explain what is meant by a signal molecule (or ligand) and, in a general way, explain the effect of signal molecules on target cells. Know that the transmission of nerve impulses at synapses, immune responses, and hormonal regulation all involve cell signalling.	139
☐	2	Identify types of signalling molecules and their roles in regulating the development, behaviour, and physiology of organisms.	140
☐	3	Understand what is meant by a hormone and describe how hormones are produced and distributed to target cells. Explain why only target cells are affected by a specific hormone whereas other cells are unaffected.	139
☐	4	Explain how a cell's sensitivity to a specific hormone is directly related to the number of receptors it displays for that hormone. Interpret diagrams of upregulation and downregulation and predict the effects of each.	139
☐	5	Recognise that the stimulus for release of a hormone may be a substance in the blood (humoral), a nerve impulse (neural), or another hormone (hormonal). If you can, give an example of each.	141
☐	6	Using an example, describe the role of negative feedback in regulating the release of hormones. Using the example of blood glucose regulation, explain how some hormones work antagonistically to control a homeostatic process.	141 145



Signal transduction

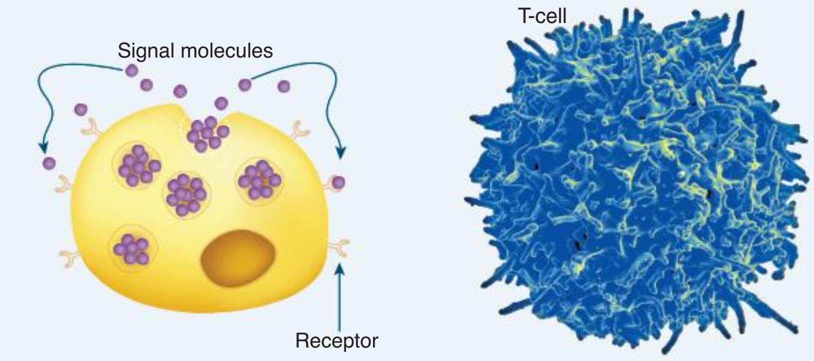
Key skills and knowledge

☐	7	Describe the stimulus-response model with respect to cell signalling to include reception, transduction, and cellular response.	142
☐	8	Distinguish between signal transduction involving hydrophilic signals (e.g. adrenaline) and hydrophobic signals (e.g. steroids such as cortisol). Include reference to differences in how the signal molecule is received by receptors and how transduction is initiated.	143
☐	9	For hydrophilic signal molecules, recognise the role of G protein-coupled receptors, second messengers, and phosphorylation cascades in producing the cellular response (names of molecules not required).	143 144
☐	10	For hydrophobic signal molecules, recognise the role of nuclear receptors (transcription factors) which are activated when the signal molecule binds.	143
	SHE	Explain how hormones are used in the dairy industry to increase production and reduce costs. Discuss the risks and ethical concerns with this practice.	146

139 Types of Cell Signalling

Key Idea: Cells use signals (chemical messengers) to communicate and to respond to changes in their environment.

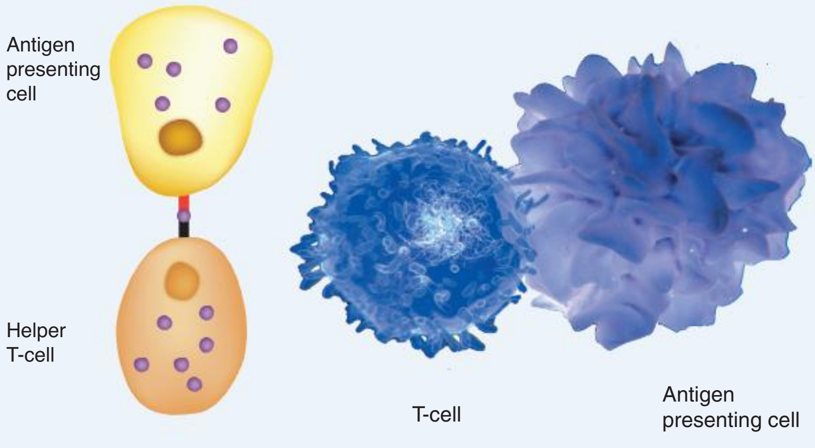
In order to communicate and respond to changes in their environment, cells must be able to send, receive, and process signals. Chemical signals are called **signal molecules** or ligands. In order for a signal to have an effect on a cell it must be able to bind to the cell and bring about a response. Cells with the receptors to bind a particular signal molecule are called **target cells** for that signal. If a cell does not have the specific receptor, then it is unaffected by the chemical signal. Cells can alter their sensitivity to a chemical signal by altering the number of receptors on the cell surface. Chemical signals can be classified based on how far they travel to cause an effect. Some act locally, others act over long distances.



Autocrine signalling

Cells can produce and react to their own signals. This type of signalling is important during growth and development and in the functioning of the immune system.

Example: In vertebrates, the presence of a foreign antibody causes T-cells to produce a growth factor to stimulate their own production. The increased number of T-cells helps to fight the infection.

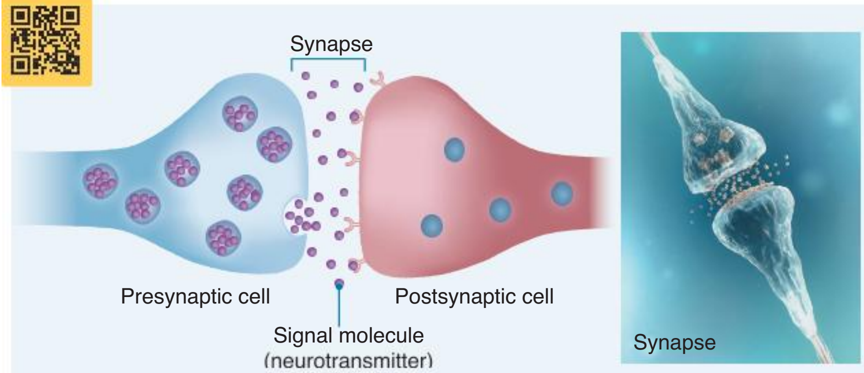


Cell-to-cell communication

Cell-to-cell communication involves cells interacting directly with one another. There are two forms: 1) communication via special channels between adjacent cells and 2) two cells bind to and communicate with each other because they have complementary proteins on their surfaces.

Example: Plasmodesmata are microscopic channels that run through the cell wall of adjacent plant cells. Signal molecules can pass through to the next cell.

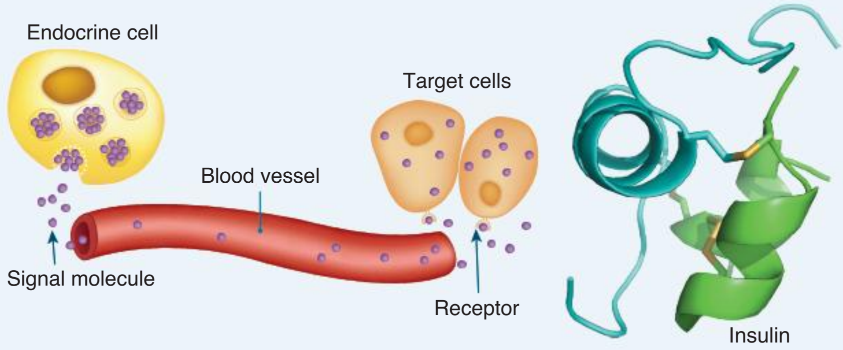
Example: In the immune system, antigen presenting cells present antigens to helper T-cells for destruction.



Signalling by local regulators

Some cell signalling occurs between cells that are close together. The signal molecule binds to receptors on a nearby cell causing a response. Both neurotransmitters and cytokines (small molecules produced by a range of different cells) are involved in this type of local regulation.

Example: Neurotransmitters released from a nerve cell travel across the synapse (gap) to another cell to cause a response.



Endocrine signalling

A signal is carried in the bloodstream to target cells, often some distance away. Endocrine signalling may involve hormones (released from the cells of endocrine glands) or cytokines as the signalling molecule although cytokines are also important in local regulation and circulate in more variable concentrations than hormones.

Example: Insulin from the pancreas stimulates the cellular uptake of glucose.

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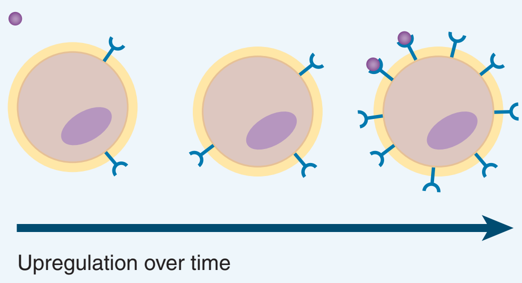
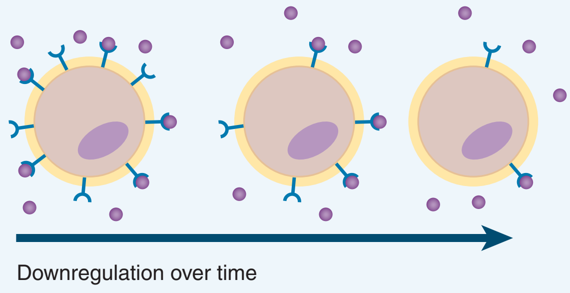
Upregulation and downregulation

A cell's response to a chemical signal, such as a hormone, not only depends on the presence of the correct receptor, but also on the number of receptors present. The more receptors a cell has for a specific signalling molecule, the greater the cellular response. The increase in a cell's response to a stimulus is called **upregulation**, whereas a reduced response to a stimulus is called **downregulation**.





Upregulation increases a cell's sensitivity to a specific hormone. It can occur by production of more receptors, or by decreasing the rate at which existing receptors are broken down. Upregulation generally occurs when the concentration of a signal molecule is very low. An increased number of receptors increases the chances of interacting with the signal to bring about a response.

Example: During the last trimester of pregnancy there is an increase in uterine oxytocin receptors. Binding of oxytocin induces uterine contraction during labour helping to expel the fetus.

Downregulation decreases a cell's sensitivity to a signal molecule. Receptor numbers are decreased by reducing the production of receptor proteins or increasing the rate at which existing receptors are broken down. This reduces the receptors available to interact with the signal molecule. Downregulation protects against receptor over-stimulation. It generally occurs when the levels of a signal molecule are very high or when there has been long term exposure to a particular signal molecule.

Example: Prolonged high blood glucose decreases insulin production in people with type 2 diabetes (insulin resistance).

1. Explain the purpose of cell signalling: ______________________________

2. Identify the components shared by all types of communication involving chemical signalling: ______________________________

3. (a) How can a cell alter its response to a signal molecule? ______________________________

(b) Use examples to contrast upregulation and downregulation and explain why these mechanisms are important:

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140 Signalling Molecules

Key Idea: Signalling molecules are widespread in nature. The effect they have is highly varied and they may act over short or long distances to cause a response.

Signalling molecules bind to specific receptors to cause a response in a target cell. There are a huge number of different signal molecules, and each has a specific effect. Some (such as hormones) tend to be slow acting and long lasting, while others (such as neurotransmitters) take effect rapidly, but the effect is short lived as the chemical is quickly broken down. Most signals affect cells within the organism, but pheromones are secreted into the environment and may travel over long distances to influence members of the same species.

Gibberellins break dormancy in seeds

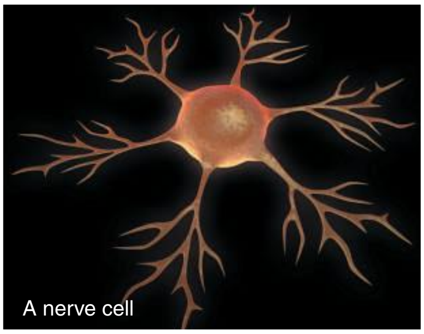
Plant hormones (phytohormones) have important roles in plant growth and development (e.g. stem elongation, breaking dormancy, and fruit fall). Plant hormones are transported around the plant by the plant's vascular tissue. They often work together and the response varies depending on the relative concentrations of each.

Hormones help animals prepare for and adjust to seasonal changes

In mammals, hormones are secreted by endocrine glands (e.g. the pituitary) and carried in the blood to target cells. Hormones are very potent, and effective at low concentrations. Hormonal responses tend to be slow (because it takes time for the signal to reach its target) and generally long lasting because they induce metabolic changes.

Lymphocytes produce cytokines

Cytokines are a large group of peptides and small proteins involved in coordinating the response of cells in the immune system both within their immediate vicinity or over large distances. Cytokines are produced by a wide range of cells, including immune cells and endothelial cells. They include interferons, interleukins, and tumour necrosis factors.



A nerve cell

Neurotransmitters are chemicals that carry signals between nerve cells or between a nerve cell and another type of cell such as a muscle or gland. Neurotransmitters act on the cell immediately next to it. They are released into a synapse (gap between the cells) and bind to receptors on the receiving cell. The response is rapid and short lived.

A bee swarm

Sichy007 cc2.5

Stallion exposing receptors

Pheromones are chemical signals released into the external environment. They are widely used by many animals, especially social insects and mammals. Pheromones have different purposes (e.g. aggression, aggregation, reproduction, territoriality) but all act to generate a specific response in members of the same species (conspecifics). A gland at the base on the honeybee abdomen secretes Queen Mandibular Pheromone, which attracts worker bees to swarm. This behaviour is important when establishing a new hive. In mammals, pheromones are used to signal sexual receptivity and attract mates. Special receptors in the nasal cavity detect the pheromones. Mammals often curl the upper lip (flehmen) to expose the receptors.

1. Compare how hormones are transported in plants and animals: ______________________________

____

2. (a) Identify a type of long lasting chemical signal: ______________________________

(b) Identify a type of short lasting chemical signal: ______________________________

3. What are the benefits of using both short and long acting signals when coordinating physiology and behaviour?

____

____

____

4. How do pheromones differ from the other types of chemical signals? ______________________________

____

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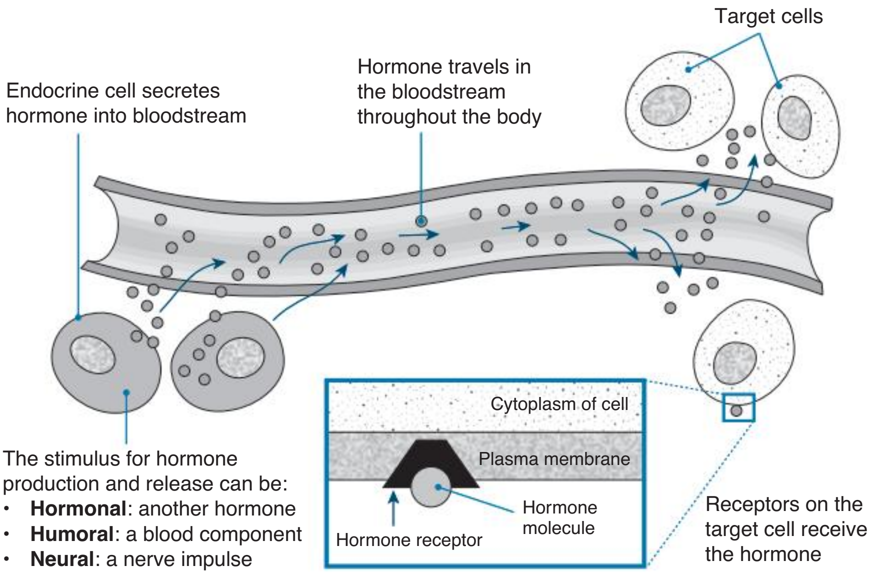
141 How Hormones Work

Key Idea: The endocrine system regulates physiological processes by releasing blood-borne chemical messengers called hormones, which interact with target cells.

Endocrine signalling has an important role in maintaining homeostasis. The endocrine system is made up of endocrine cells (organised into endocrine glands) and the hormones they produce. Hormones are potent chemical regulators. They are produced in very small quantities but can exert a very large effect on metabolism. Endocrine glands secrete hormones directly into the bloodstream rather than through a duct or tube. The basis of hormonal regulation through negative feedback is described below.

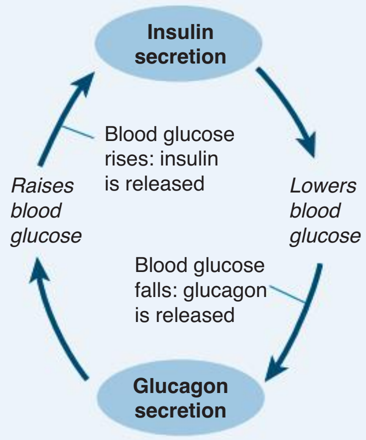
How hormones work

Endocrine cells produce hormones and secrete them into the bloodstream where they are distributed throughout the body. Although hormones are sent throughout the body, they affect only specific target cells. These target cells have receptors on the plasma membrane which recognise and bind the hormone (see inset, below). The binding of hormone and receptor triggers the response in the target cell. Cells are unresponsive to a hormone if they do not have the appropriate receptors.



The stimulus for hormone production and release can be:
- **Hormonal**: another hormone
- **Humoral**: a blood component
- **Neural**: a nerve impulse

Antagonistic hormones



The effects of one hormone are often counteracted by an opposing hormone. Feedback mechanisms adjust the balance of the two hormones to maintain a physiological function.

Example: insulin acts to decrease blood glucose and glucagon acts to raise it.

1. (a) What is a hormone? ____________________

(b) Why can a hormone only influence specific target cells even though all cells may be exposed to the hormone?

____

2. (a) Describe how antagonistic hormones act to maintain homeostasis: ____________________

(b) What is the stimulus for the release of insulin? Humoral / Hormonal / Neural (circle one)

(c) Use the example of blood glucose to explain the role of feedback mechanisms in adjusting hormone levels:

____

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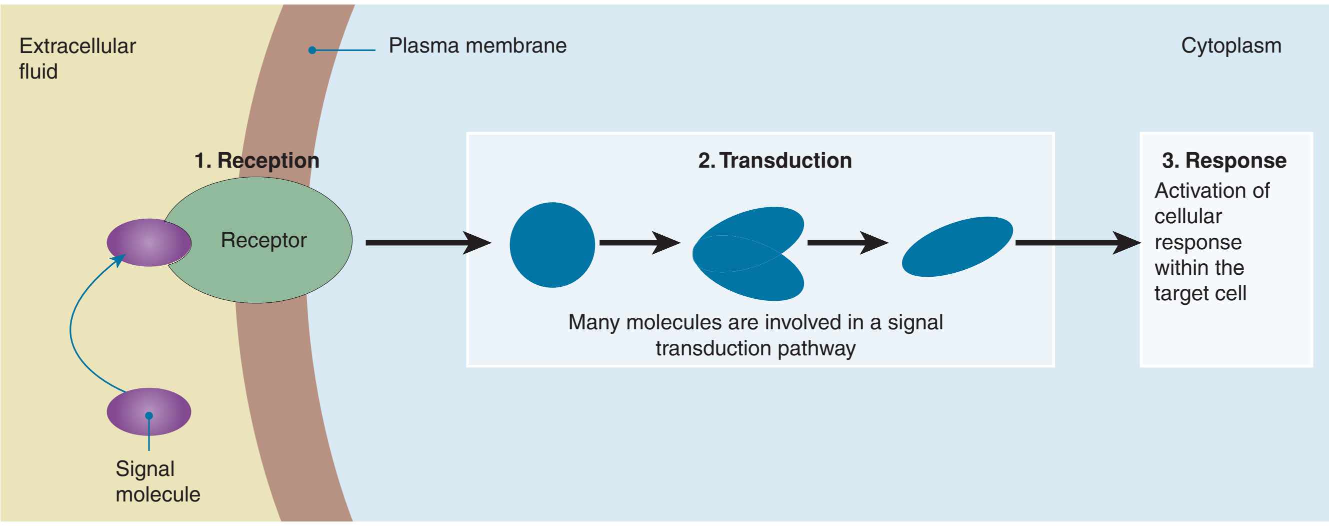
142 What is Signal Transduction?

Key Idea: Signal transduction is the conversion of an external signal to a functional change within the cell through a series of biochemical reactions.

Signal transduction is the process by which molecular signals are transmitted from outside the cell to inside, bringing about a cellular response. The transduction involves an external signal molecule binding to a receptor and triggering a series of biochemical reactions, which lead to a specific cellular response. The series of biochemical reactions is often called a cascade and usually involves phosphorylation (charging) of a number of molecules in a sequence. The type of response varies and may include a change in metabolism (activating a pathway), gene expression (to produce a specific protein), or membrane permeability (to allow entry of specific molecules).

An overview of signal transduction

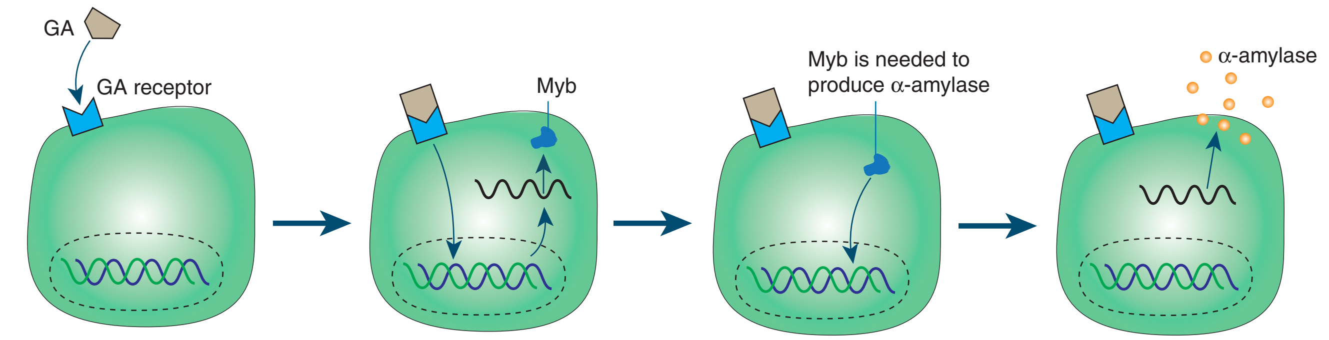


Signal transduction can be broken into three main steps:

- **Reception**: An extracellular signal molecule binds to its receptor on a target cell.
- **Transduction**: The activated receptor triggers a chain of biochemical events within the cell. Many different enzymes are involved, and the entire reaction is often called a signalling cascade.
- **Response**: The signal cascade results in a specific cellular response.

Gibberellic acid activation of α-amylase: An example of a cellular response

In plants, the hormone gibberellic acid (GA) is involved in seed germination. GA acts as a signal molecule to stimulate the production of the enzyme α-amylase. The α-amylase hydrolyses (breaks down) starch into simple sugars, which the plant can use.



GA binds to a receptor on the plasma membrane.

GA receptor signals for the production of a transcription factor called Myb protein.

Myb protein binds to DNA and activates transcription of α-amylase enzyme.

α-amylase is produced and hydrolyses the starch in the seeds into simple sugars.

1. Name the three stages of signal transduction and describe what occurs at each stage:

(a) ______________________________

____

(b) ______________________________

____

(c) ______________________________

____

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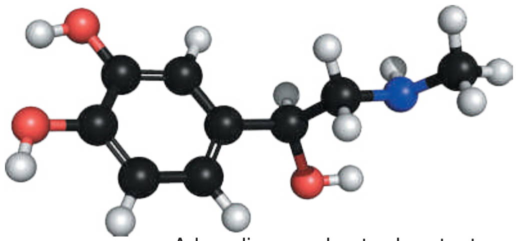
143 Types of Signal Transduction

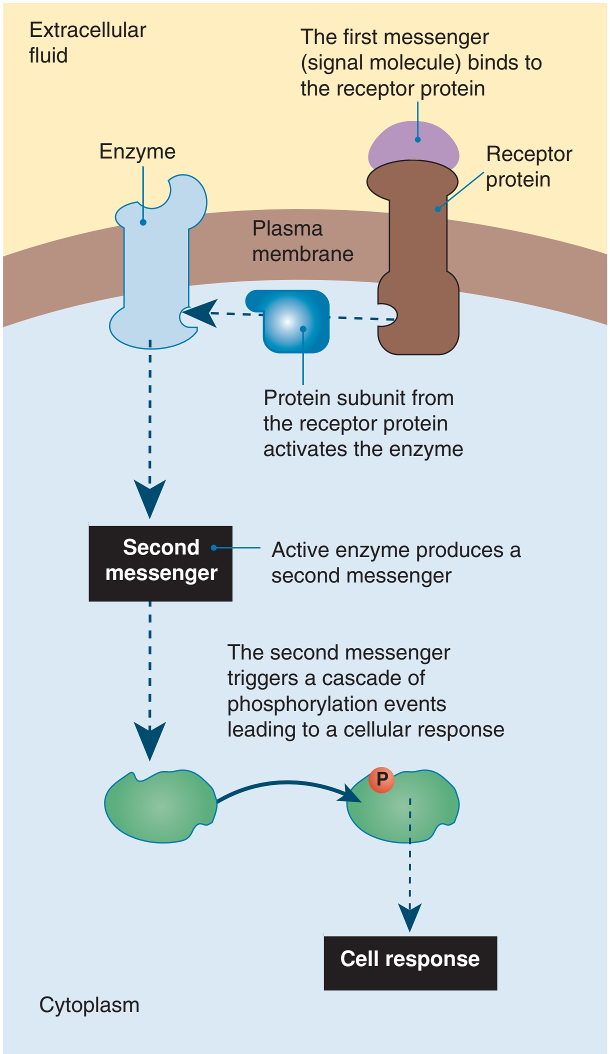
Key Idea: The majority of cell signals bind to extracellular receptors to exert their effect. However some cell signals are able to pass through the plasma membrane and bind directly to intracellular receptors within the cell to exert their effect.

Cell receptors fall into two broad classes. **Extracellular receptors** bind signal molecules outside of the cell. The signal molecule does not have to pass across the plasma membrane to cause a cellular response. Most cell receptors are extracellular receptors. **Intracellular receptors** bind signal molecules that have passed into the cell directly across the plasma membrane. Intracellular receptors may be located in the cytoplasm or on the nucleus.

Hydrophilic signal molecules are received by extracellular receptors

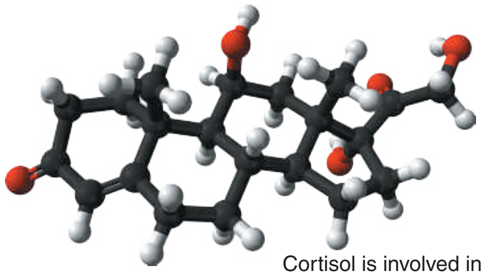


Adrenaline accelerates heart rate and is involved in the fight or flight response

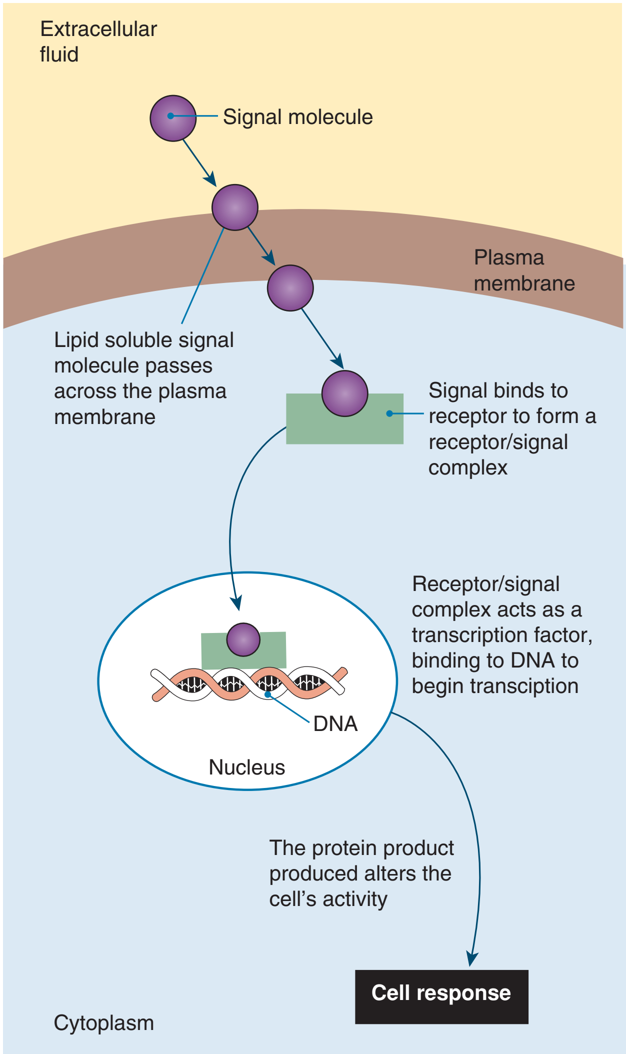


Hydrophilic signal molecules are water soluble and so cannot cross the plasma membrane. They exert their effect via an extracellular receptor. Hydrophilic signals include water soluble hormones such as adrenaline. The signal molecule is the first messenger. Binding activates the extracellular receptor, triggering a sequence of biochemical reactions, including activation of a second messenger. As a result, the original signal is amplified, and there is a cellular response.

Hydrophobic signal molecules are received by intracellular receptors



Cortisol is involved in glucose metabolism and response to stress



Hydrophobic signal molecules diffuse freely across the plasma membrane and into the cytoplasm of target cells. In the example above the signal molecule binds to a receptor in the cytoplasm to form a receptor/signal complex. The complex moves to the cell nucleus where it acts as a **transcription factor** to control the expression of specific genes. Steroid hormones, such as cortisol and sex hormones, are examples of hydrophobic signal molecules.

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1. Describe the differences between an intracellular receptor and an extracellular receptor: ______________________

2. What must a signal molecule do in order to activate a receptor? ______________________

3. In terms of their ability to cross the plasma membrane, describe the difference between a hydrophobic signal molecule and a hydrophilic signal molecule:

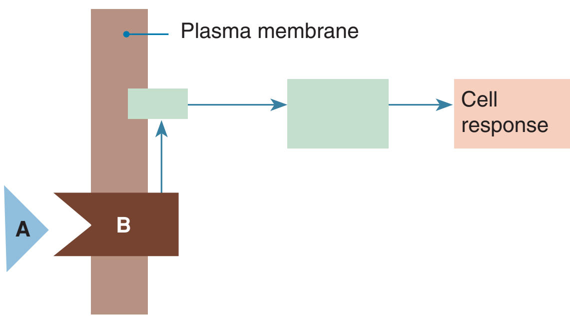
4. (a) Outline the process when signal transduction occurs via an extracellular receptor: ______________________

   (b) Describe the differences between a first messenger and a second messenger: ______________________

5. Outline the process when signal transduction occurs via an intracellular receptor: ______________________

6. The diagram on the right represents a cell signalling process.

   (a) Does this diagram represent an extracellular or intracellular signalling process? Explain your answer:



   (b) What type of receptor is B? ______________________

   (c) What does A represent? ______________________

   (d) Would A be hydrophobic or hydrophilic? Explain your answer: ______________________

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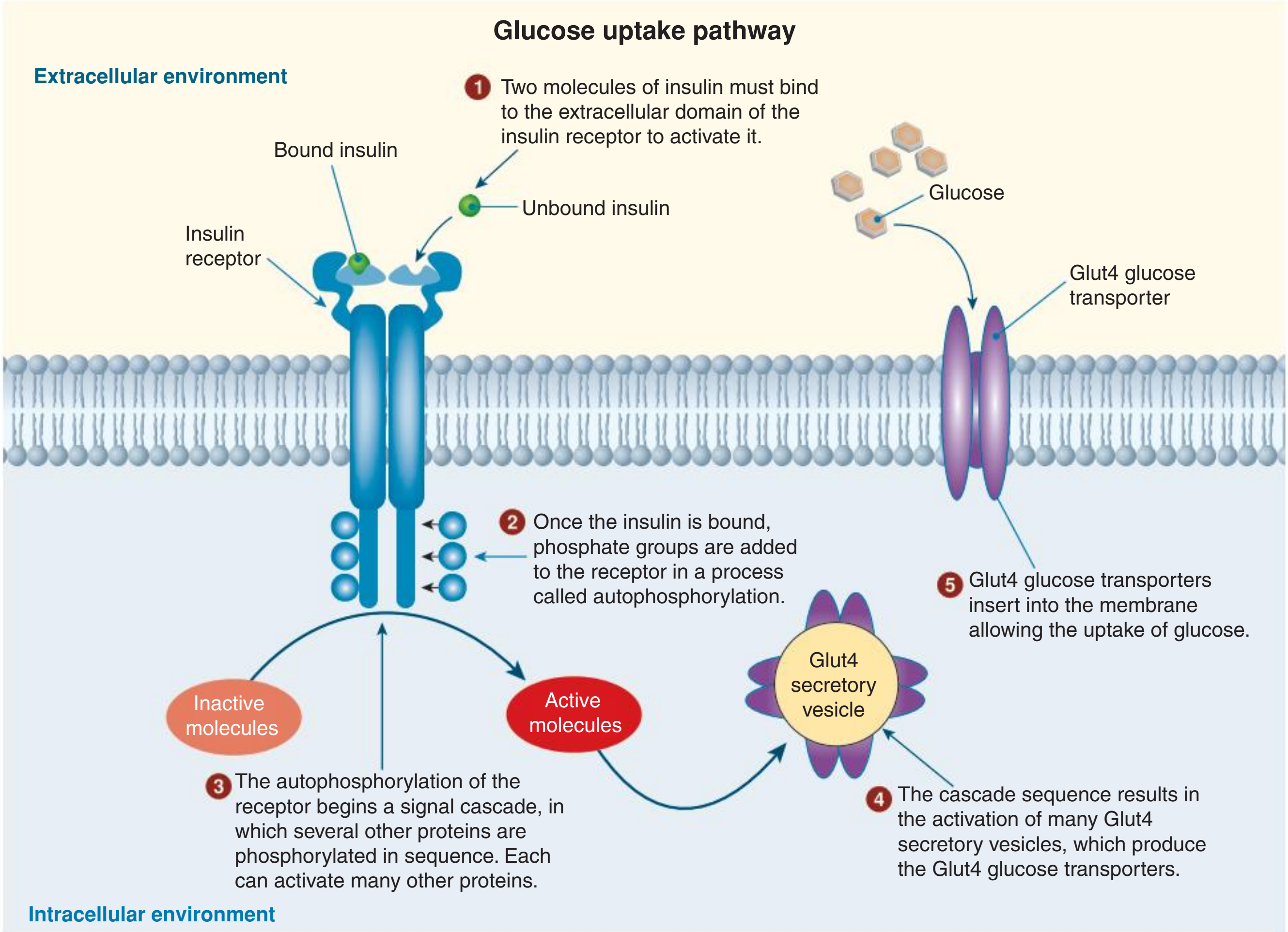
144 Action of Insulin

Key Idea: Activation of the insulin receptor by insulin causes a signal cascade that results in cellular glucose uptake.

Insulin is a peptide hormone secreted by the pancreas. It is involved in regulating blood glucose levels by promoting the uptake of glucose by cells. Malfunctions in the signaling pathways for insulin production and reception have serious physiological consequences (including death) so these are tightly regulated and under strong selection (evolutionary) pressure. If insulin is lacking or cells fail to respond to it, blood glucose remains elevated while the body's cells themselves are starved of fuel. Insulin circulates in the blood where it binds to protein kinase receptors on the surface of cells and triggers a signal cascade that results in activation of the membrane transporters that bring glucose into the cell.



1. (a) What type of signaling does this example represent (circle one): autocrine / local regulation / endocrine / pheromone

   (b) Explain why you chose this answer: ______________________________

2. Why must blood glucose levels be tightly regulated? ______________________________

3. Describe the process by which insulin signaling causes the uptake of glucose into cells: ______________________________

4. How does the signal cascade increase the response of the insulin receptor? ______________________________

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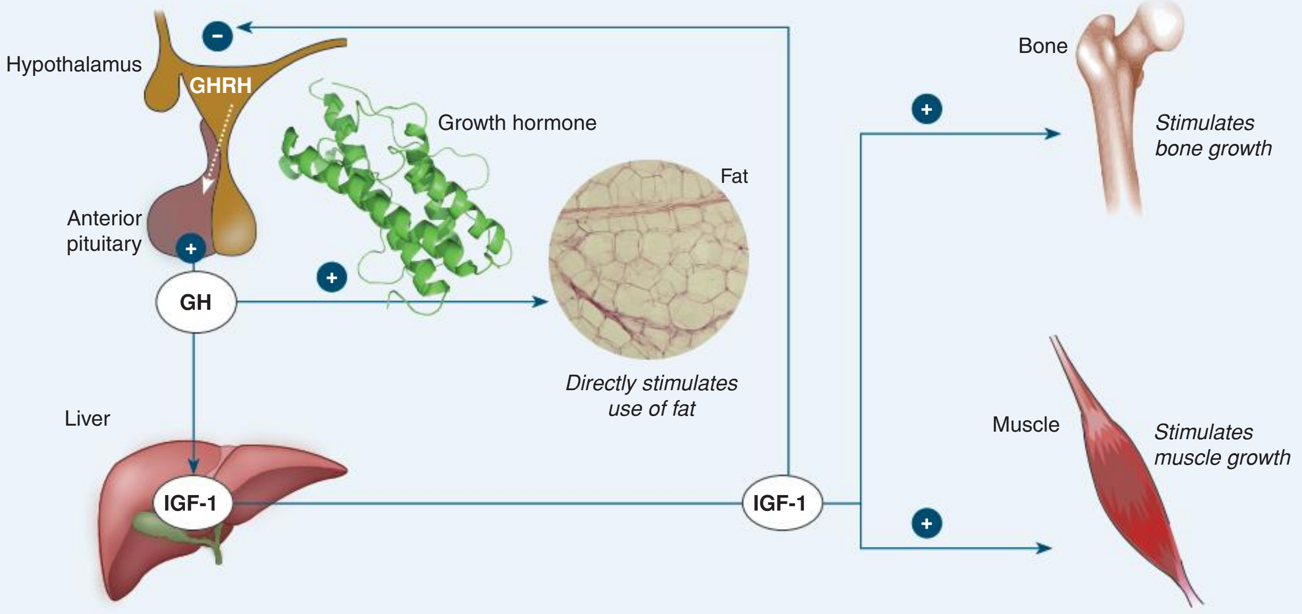
145 Hormones are Regulated by Negative Feedback

Key Idea: Growth hormone is required for normal growth and development. Its levels are tightly regulated through negative feedback mechanisms to prevent growth disorders.

Growth hormone (GH) is a peptide hormone that stimulates growth, cell reproduction, and cell regeneration through endocrine signalling. GH is released from the pituitary gland at the base of the brain and circulates in the blood where it binds to two adjacent receptors on liver cells and stimulates the production of a protein called insulin-like growth factor (IGF-1). GH levels are regulated by negative feedback (a regulatory mechanism in which a stimulus input causes an opposite output in order to maintain a steady state). GH has a critical role in human development and malfunctions in its regulation can result in a number of serious conditions including growth deficiencies (low GH) and abnormal tissue growth resulting in tumours or giantism (excessive GH).

The effects and regulation of growth hormone

- Growth hormone (GH) is released in response to GHRH (growth hormone releasing hormone) from the hypothalamus of the brain. GH acts both directly and indirectly to affect metabolic activities associated with growth.
- GH directly stimulates metabolism of fat, but its major role is to stimulate the liver and other tissues to secrete IGF-1 (Insulin-like Growth Factor 1) and through this stimulate bone and muscle growth.
- GH secretion is regulated via **negative feedback**. High levels of IGF1 suppress GHRH secretion (and therefore GH secretion from the anterior pituitary).



1. Describe the metabolic effects of growth hormone: ______________________

2. What is the role of negative feedback in regulating the secretion of growth hormone?

3. In a separate but related control pathway, high levels of IGF-1 also stimulate the release of GHIH, an inhibiting hormone from the hypothalamus. GHIH suppresses secretion of GH. In the space on the right, construct a negative feedback pathway to show how GHIH regulates GH secretion:

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146 Use of Hormones in the Dairy Industry

Key Idea: Recombinant bovine somatotropin (rBST) can be injected into dairy cows to increase milk production. However, there are numerous concerns about its effects on livestock and its use is not permitted in Australia.

Cows produce hormones naturally, some of which promote growth and influence milk production. In some countries, synthetic (man made) versions of these hormones are used by farmers to promote livestock growth or increase milk production in dairy cows. An example of this is recombinant bovine somatotropin (rBST), also called recombinant bovine growth hormone (rBGH). However, there are concerns over the welfare of animals injected with rBST and its use is banned in some countries. Several countries, including Australia, do not allow rBST to be used in dairy cows.

rBST

- Bovine somatotropin (BST) is a hormone produced naturally in cows from the anterior pituitary (a gland at the base of the brain). BST is important in normal growth and development.
- In the 1930s and 1940s, BST researchers found that BST extracted from the pituitary gland of dead cows and injected into cows increased milk production.
- In the 1980s, recombinant BST (rBST) was produced using biotechnology methods, allowing large quantities of rBST to be produced in *E.coli* bacteria.
- The first commercial sales of rBST in the USA occurred in 1993.

Pros and cons of using rBST

BST regulates milk production in lactating cows by directing more nutrients to be utilised to make milk. This increases milk production. Usually milk production peaks 60-90 days into lactation and then begins to fall. However, peak production can be extended by injecting cows with rBST. The use of rBST:

- Increases milk production by 10-15%.
- Increases the efficiency of milk production.
- Decreases the environmental impact of dairy farming (through improvements in productivity and efficiency).
- Reduces the economic cost of dairying.
- Although some potential health effects in humans have been raised (e.g. increased risk of cancer) as yet there is no evidence linking rBST to negative health effects in humans. The fact that the hormone is destroyed in the human gut is considered to reduce any potential health risks.

Some countries (e.g. the USA) permit the use of rBST in dairy herds. However, its use is banned in several countries (including Australia) because of animal heath issues. These include:

- 24% increase in mastitis (painful inflammation of the mammary gland). Mastitis (right) is treated by antibiotics and could contribute to increasing antibiotic resistance.
- 40% reduction in fertility.
- 55% increase in lameness.

Mohammad Golkar cc4.0

1. (a) What affect does BST hormone have on milk production? ______________________

   (b) Describe how it exerts its effect: ______________________

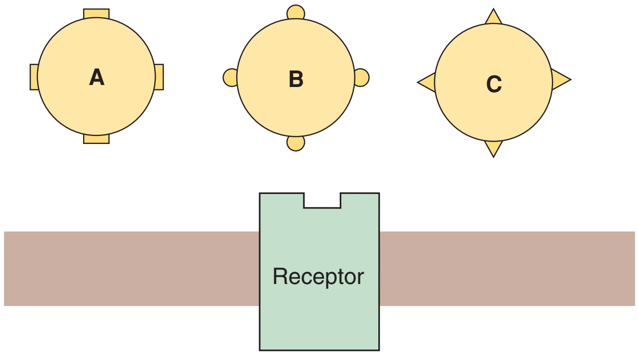
2. Discuss the advantages and disadvantages of using rBST in the dairy industry and decide if you think its ban in Australia is justified.

SHE 110

ISBN: 978-1-927309-83-4

147 KEY TERMS AND IDEAS: Did You Get It?

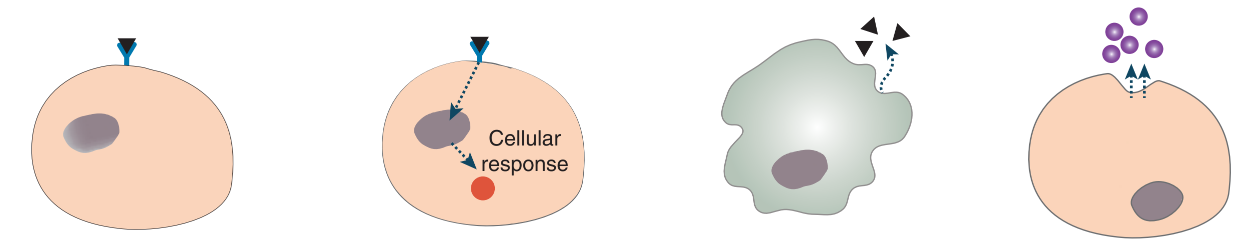
1. (a) The molecules labelled A-C are signalling molecules. Identify the signal molecule that will bind to the receptor shown:



(b) What prevents the other two signal molecules from binding to this receptor?

(c) Why is it important that not all cells react to every signal molecule?

2. In the space below, label the sequence (1-4) in the correct order and briefly describe what is happening at each stage:



3. Choose the correct answer from the choices below:

Hormones are relatively long lived signals, which travel through the blood. This type of signalling is called:

(a) Autocrine signalling
(b) Cell-to-cell communication
(c) Local regulation
(d) Endocrine signalling
(e) Pheromone signalling

4. Choose the correct answer from the choices below:

What type of signal molecule is used in synaptic signalling?

(a) Hormones
(b) Neurotransmitters
(c) Pheromones
(d) Cytokines

5. Match each term to its definition, as identified by its preceding letter code.

Term		Code	Definition
extracellular receptor		A	A chemical molecule that binds to a cellular receptor and brings about a change within the cell.
hormone		B	A cell that responds in a particular way to a specific signal molecule.
intracellular receptor		C	A receptor located within a cell.
signal molecule		D	A receptor that spans the plasma membrane.
signal transduction		E	The transmission of molecular signals from the exterior to the interior of the cell.
target cell		F	A blood-borne chemical signal released from endocrine glands.

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UNIT 2
Topic 1

Thermoregulation

Key terms

aestivation
endotherm
hibernation
insulin
kleptothermy
panting
sweating
thermogenesis
thermoregulation
thyroid hormone
thyroxine
torpor
vasoconstriction
vasodilation

Activity number

Thermoregulation

Key skills and knowledge

- ☐ 1 Explain what is meant by thermoregulation. Describe the different challenges that air and water present to animals that must thermoregulate. How does the environment determine the strategies they use? **148**
- ☐ 2 Understand the difference between ectotherms (e.g. lizards), which rely on heat from the environment for their body heat, and endotherms (birds and mammals), which generate their body heat through metabolism. **148**
- ☐ 3 Know that endothermic homeotherms maintain a (usually high) constant body temperature using the heat generated from metabolism. Relate this to the high energy demands of endotherms (relative to ectotherms such as lizards). **149**



lamnotanorange-commonswiki cc2.5

Thermoregulatory responses

Key skills and knowledge

- ☐ 4 Identify structural, behavioural, and physiological mechanisms directly or indirectly related to thermoregulation (and its energy costs) in endotherms. Recognise that many thermoregulatory mechanisms involve aspects of structure, behaviour, and /or physiology, e.g. structures such as large ears (structural) may be used in a certain way (behavioural) or their blood flow altered (physiological) in order to regulate temperature. **148**

Structural mechanisms

- ☐ 5 Describe and explain structural mechanisms for thermoregulation, including the role of insulation (fat, blubber, hair, fur, feathers) in the retention of body heat and in preventing excessive heat load. How do animals carry their fat stores and change the insulating capacity of their body coverings to assist temperature regulation in different environments? **149**

Behavioural responses

- ☐ 6 Understand that thermoregulatory behaviours in endotherms are related to reducing the energetic costs of maintaining a constant temperature. The simplest include basic behaviours such as drinking and seeking shade or warmth. **150**
- ☐ 7 Identify thermoregulatory behaviours in endotherms, including kleptothermy (e.g. huddling), and behaviours that enable animals to offset the high energetic costs of thermoregulation at certain times of the year (hibernation, aestivation, and torpor). **150**
- ☐ 8 Using examples, describe and explain hibernation, aestivation, and torpor. When are these strategies used and why are they relatively more common in small endotherms with high metabolic rates and high surface area to volume ratios? **150**

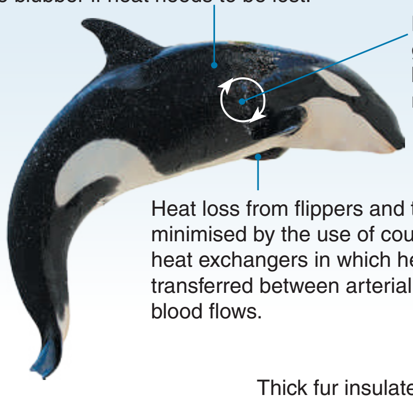
Physiological mechanisms

- ☐ 9 Using examples, describe and explain physiological mechanisms for thermoregulation including autonomic (vasomotor) control of blood flow (vasoconstriction and vasodilation), evaporative heat loss from body surfaces, countercurrent heat exchangers, and thermogenesis (heat production from metabolism including from metabolism in brown fat). **151**
- ☐ 10 Explain the role of hormones (thyroid hormones and insulin) in regulating the metabolic generation of heat. Recall that negative feedback regulates hormone levels and explain this in terms of the thyroid hormone thyroxine (T4). **152**
- ☐ 11 SHE Describe how models of human thermoregulatory responses can be used in the design of clothing, environments, and safety regulations. **153**

148 Mechanisms for Thermoregulation

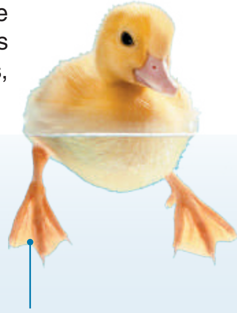
Key Idea: Endotherms regulate their body temperature to within narrow limits by controlling heat exchanges with the environment and generating heat from metabolism. This is termed thermoregulation.

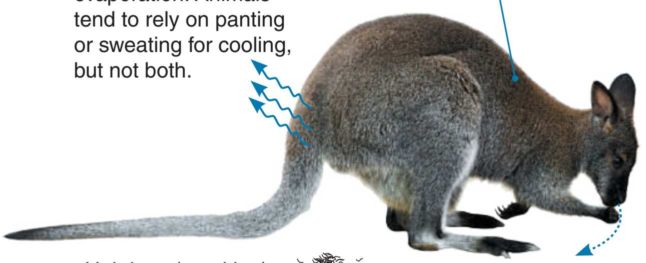
Heat exchanges with the environment occur via conduction, radiation, and evaporation. To maintain a relatively constant body temperature, endotherms must balance heat losses and gains. Thermoregulation is achieved through a variety of mechanisms: structural (physical attributes of the body), behavioural (the way an organism behaves), and physiological (mechanisms at the metabolic level). These mechanisms allow an organism to maintain a body temperature that is optimum for functioning. For endotherms, generate their body heat through metabolism, thermoregulation represents a high energy cost.



Temperature regulation mechanisms in water

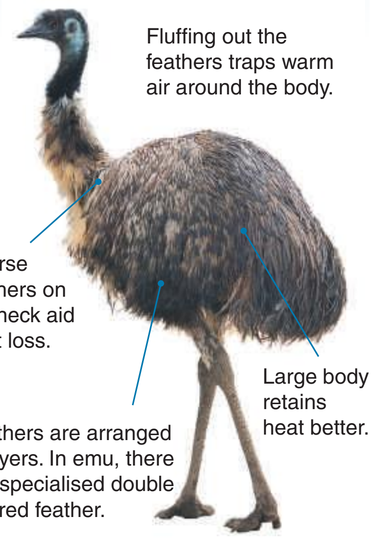
- Heat generation from metabolic activity
- Insulation layer of blubber
- Changes in circulation patterns when swimming
- Large body size
- Heat exchange systems in limbs or high activity muscle





Temperature regulation mechanisms in air

- Behavior or habitat choice
- Heat generation from metabolic activity, including shivering.
- Insulation (fat, fur, feathers)
- Circulatory changes including constriction and dilation of blood vessels
- Large body size
- Sweating and panting
- Tolerance of fluctuation in body temperature



For most mammals, the thickness of the fur or hair varies around the body. Thermoregulation is assisted by adopting body positions that expose or cover areas of thin fur and help regulate heat loss or gain.

In birds, short, fluffy feathers (down) provide insulation against cold. Aquatic birds have waterproof, tightly packed feathers to reduce water entry and aid insulation. In the emu, the black tipped feathers capture heat while lighter feathers underneath insulate the body. This allows the bird to be active in the hot parts of the day without overheating.

1. Endotherms use a number of different mechanisms to thermoregulate, although not every mechanism is present in every species. Determine if the following are structural, behavioural, or physiological mechanisms:

(a) Seeking shade: ____________________

(b) Countercurrent heat exchange systems: ____________________

(c) Presence of fur, feathers or hair: ____________________

(d) Presence of a blubber layer: ____________________

(e) Generation of heat through metabolism: ____________________

(f) Panting: ____________________

(g) Alteration of circulation pattern: ____________________

(h) Reduced activity at hot temperatures: ____________________

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149 Structural Features for Thermoregulation

Key Idea: Structural features for thermoregulation are those involving how the animal is built, such as long or short ears, blubber, or fur.

Structural mechanisms for thermoregulation are those that arise from the physical structure of the animal, its size and build and features of the skin and body coverings. A common structural feature for thermoregulation in mammals is fur (except in some marine mammals). In birds, this role is taken by feathers. Physiological adaptations usually accompany structural features, such as the ability to moult from a winter to summer coat and the ability to raise and lower the hair or feathers to increase or decrease insulation.

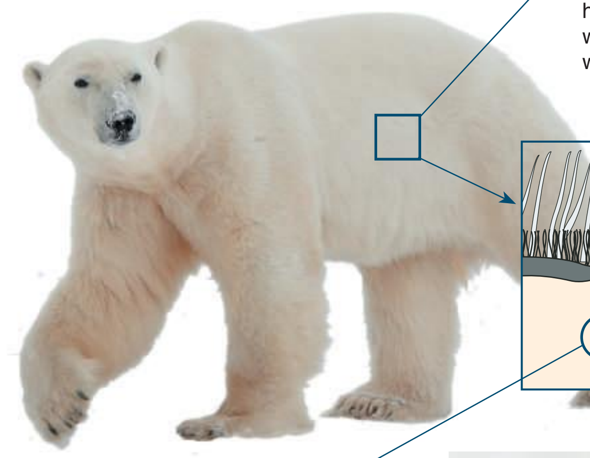
Keeping warm

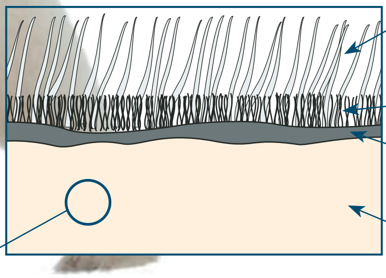
Preventing heat loss is important for small animals and those in very cold environments. This includes animals that live in the polar regions and marine animals.

Fur

Fur (hair) is a mammalian characteristic. It is a very good insulator in terrestrial environments. There is often a double layer of fur, an outer long layer and an inner (and very thick) insulating layer. Oils in the fur help to waterproof it. Both fur and feathers work by trapping air close to the body, warming it and preventing it escaping.

Sea otters are one of the furriest mammals with more than 124,000 hairs per cm^2 in their inner coat.





Polar bear fur

Guard hairs: Long and transparent. Scatter light, enhancing camouflage but also allow some light through to heat the skin.

Dense underfur: Traps air and prevents body heat from escaping.

Dark pigment: Helps the absorption of heat from sunlight.

Fat layer: Thick fat layer aids insulation especially when swimming, when the fur loses much of its insulation value.

Blubber and fat

Blubber is found in marine mammals including whales and seals. It is highly vascularised (many blood vessels) fat tissue just below the skin and surrounds most of the body, acting as a thermal insulator. The higher the lipid concentration in the blubber the better its effect as an insulator. Fat is less vascularised and has less structure but acts in a similar way by trapping heat in the body.

Feathers

Feathers evolved primarily as insulation rather than as a flight surface. They still carry out the function of insulation exceedingly well. Down feathers (left) are found below the outer feathers. They are such effective insulators that birds such as emperor penguins are at risk of over heating when out of water. Down (e.g. eiderdown) is used by humans as an insulator in jackets and sleeping bags.

Keeping cool

As much as animals need to keep warm in some environments, they need to keep cool in others. Structural features to help prevent overheating include large exposed areas of highly vascularised skin, localisation of fat stores, and fur and feather colouration.

Ears

The external ears of desert mammals provide a structural mechanism to assist heat loss. Elephants, jack rabbits, and fennec foxes have huge ears relative to their body size, and the ears are covered in highly vascularised skin. As blood passes through the blood vessels it loses heat to the environment. Having large ears helps to catch a breeze which increases evaporative cooling. Elephants are able to flap their ears, further increasing their cooling ability.

Feathers

Not only do feathers keep heat in but they can be just as effective at keeping heat out. Desert birds often have dark coloured feathers, especially on their dorsal surface (back). These absorb heat near their surface, preventing it reaching the skin. A breeze, especially when flying, can then easily remove the heat. Feathers on the breast and belly are often thinner to increase heat loss. The bald head of the vulture above may also have some thermoregulatory function.

Localisation

One strategy to help lose heat is to localise fat stores and hair cover. Instead of having fat reserves evenly distributed over the body they are concentrated in certain areas, such as the back hump in camels. This reduces the insulating effect of the fat to a small region on the back (which may also help reduce heat absorption from the sun). Hair is found mainly on the dorsal surface to protect the skin from the sun but the belly may be relatively naked.

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1. Why are feathers good insulators?

2. How do feathers help protect a desert bird from overheating?

3. (a) In what way is blubber different from fat?

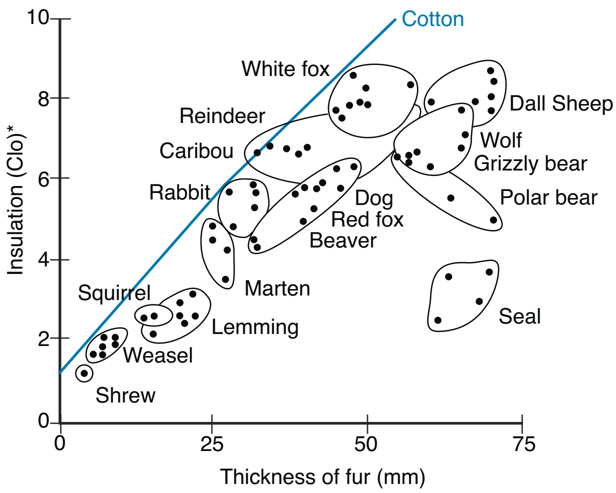
   (b) How do blubber and fat help an animal retain heat?

4. How does fur or hair help to insulate the body?

5. In what way can ears be used as thermoregulatory structures?

6. How does localising structures such as fur and fat deposits help in the regulation of body temperature?

7. Study the graph below:



Clo is the unit for clothing insulation. 1 Clo = 0.155 watts per square metre kelvin ($K{\cdot}m^{2}{\cdot}W^{-1}$)

   (a) What is the relationship between fur (hair) length and insulation effect:

   (b) Seal fur appears to provide little insulation. Why would this not affect the seal in a cold environment?

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150 Behavioural Responses for Thermoregulation

Key Idea: Thermoregulation is related to energy balance and animals have behavioural responses to reduce energy consumption when energy sources are scarce.

Animals have many different behavioural responses to help them regulate their body temperature. These may be very simple, such as moving out of the sun into the shade, or they may be more complex, such as hibernation over winter or periods of torpor. Endotherms expend large amounts of energy to maintain a high constant body temperature and high metabolic rate. Periods of reduced activity and low body temperature, such as occur during hibernation, conserve large amounts of energy and enable survival through periods when food is scarce. Such energy savings are particularly important for many small endotherms, because they lose heat very quickly and their per gram metabolic costs are much higher than for larger animals.

Bernard DUPONT CC 2.0

Regulating body temperature can be as simple as moving in or out of the shade. In some cases the shade can be carried around with you as with these cape ground squirrels.

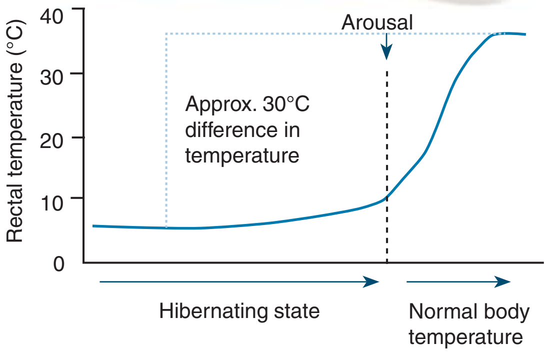
Many animals huddle together in cold conditions to conserve body heat. This behaviour is called **kleptothermy** and it occurs in both endotherms and ectotherms.

Panting evaporates water from the lining of the oral cavity. In dogs, it is an important way to lose accumulated heat because they have sweat glands only on the pads of their feet.

Hibernation

Hibernation is a prolonged (usually seasonal) state of reduced activity and metabolic depression, during which body temperature drops. It markedly reduces energy expenditure, allowing the animal to survive winter. Short daylength, low temperatures, and low food availability are strong cues for entering hibernation.

The graph (below) shows body temperature in golden hamsters during hibernation. Note the difference between the animal's normal and hibernating body temperature (~30°C). During hibernation, metabolic activity (blood flow to the brain and respiration rate) significantly decreases. It increases to a maximum during arousal and tapers off once normal body temperature is achieved. The elevated metabolic rate during the arousal period speeds up arousal and rapidly clears waste products from the body.

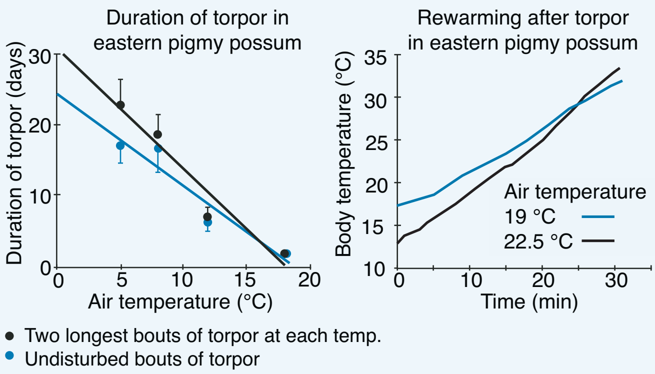


Source: Osborne http://www.asahikawa-med.ac.jp/dept/mc/phys1/profiles/osborne.html

Torpor

Some animals reduce their metabolic activity on a daily (or rather nightly) basis during their sleep. This is called **torpor**. The eastern pigmy possum is found throughout the eastern coast and south of Australia. It weighs up to 43 grams. During winter it carries out daily torpor. The period of the torpor depends on the air temperature. The possum may remain in a torpid state for up to 35 days at a time during winter hibernation and its body temperature may fall as low as 1 °C.

Phil Spark CC 2.0



Source: Australian Journal of Zoology, 1993

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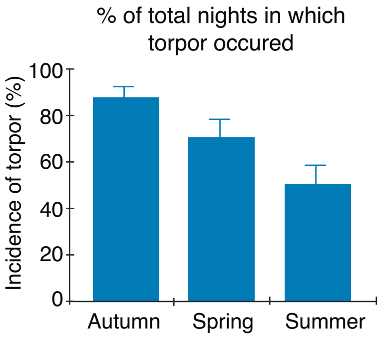
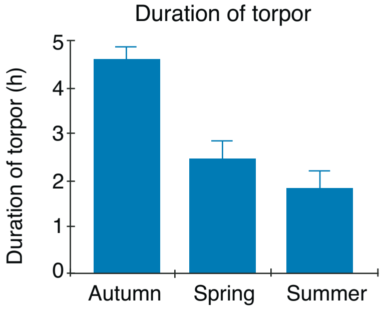
Aestivation

Aestivation is a form of hibernation or torpor that occurs during the warmer months of the year rather than the cooler months. In endothems, it is physiologically difficult to distinguish from torpor and is essentially an arbitrary label used to distinguish torpor during warmer months. It occurs in many mammals including echidnas, dunnarts (a small mouse-sized marsupial), possums, and bats. Many mammals that aestivate enter daily torpor for most months of the year and are constantly active only during the most favourable months (be they the hottest or coolest months depending on the environment). Aestivation is often a response to a lack of food in arid environments. It reduces the need to expend energy keeping cool and can reduce the amount of water lost due to evaporation (by between 20-40% in dunnarts). Aestivation also occurs in some birds, although it is much rarer. Rufous hummingbirds (below) enter a nocturnal torpor during the summer months to reduce thermoregulatory energy expenditure.





Sara Hiebert 1993

Rufous hummingbird (North America)

Ryan Bushby CC 2.5

1. What is the difference between hibernation, torpor, and aestivation? ____________________

2. (a) What are the survival advantages of hibernation? ____________________

   (b) What are the common environmental cues triggering hibernation and why? ____________________

3. (a) What happens to the body temperature of the golden hamster during hibernation? ____________________

   (b) Why does this change in temperature occur? ____________________

   (c) Explain why blood flow to the brain and respiration rate may peak during arousal from hibernation:

4. (a) How does air temperature affect the length of bouts of torpor in the eastern pigmy possum? ____________________

   (b) Why does torpor enhance survival of small endotherms in cold conditions: ____________________

5. What is often the trigger for aestivation? ____________________

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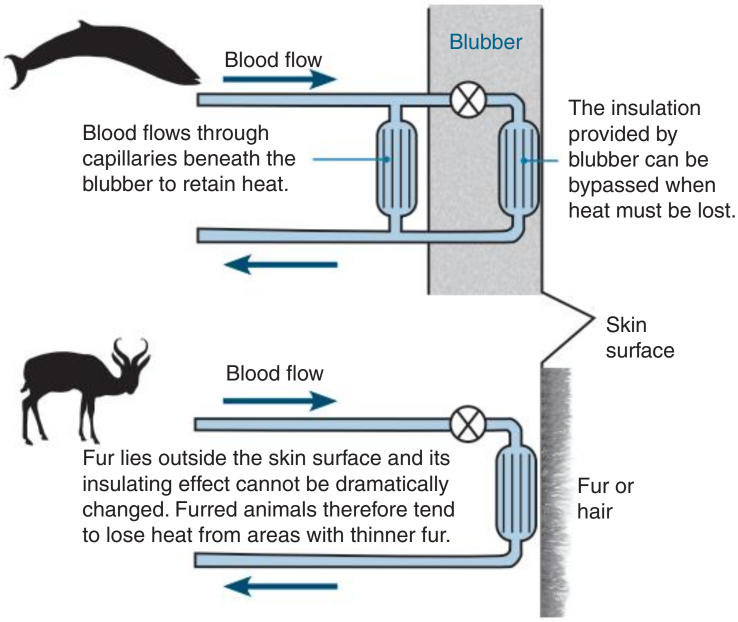
151 Physiological Mechanisms for Thermoregulation

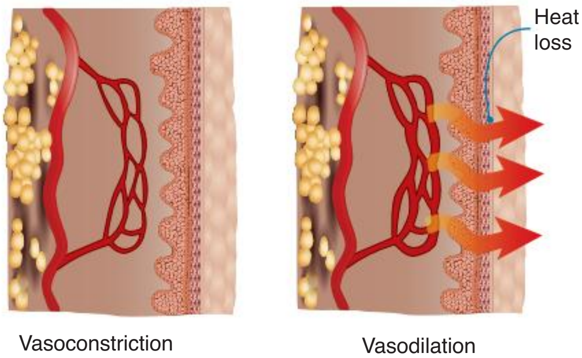
Key Idea: Temperature can be regulated and maintained by internal mechanisms that control energy use and blood flow.

Physiological mechanisms are internal mechanisms that affect how the body operates. Mechanisms of physiological thermoregulation include the use of energy resources (e.g. metabolising fat), changing aspects of metabolism (redirecting chemical reactions), and changing aspects of blood flow (vasoconstriction and countercurrent flows).

Regulating blood flow to the skin

The blubber in marine mammals provides good insulation against heat loss but presents a problem in warmer waters or during exertion when a lot of metabolic heat is generated. In these situations, blood flows through the blubber to the skin surface where excess heat is dissipated. Cold adapted land mammals have insulation outside the skin and have thinly covered areas on the face and feet, where heat can be lost during exertion.



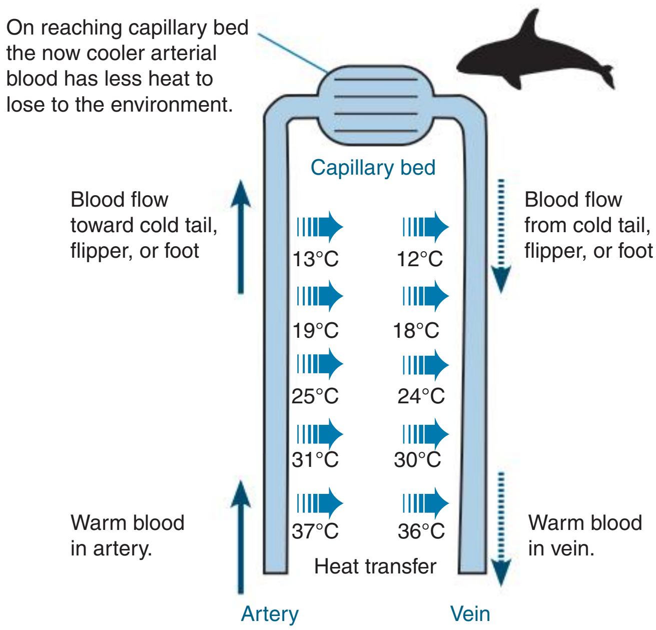


Constriction of a the capillaries (vasoconstriction) restricts blood flow. Vasodilation allows blood to flow through the capillaries and transport heat from the body to the skin.

To regulate heat loss or gain from the skin, the blood vessels beneath the skin's surface constrict (**vasoconstriction**) to reduce blood flow or dilate (**vasodilation**) to increase blood flow. When blood vessels are fully constricted, there may be as much as a 10°C temperature gradient from the outer to inner layers of the skin. Extremities such the hands and feet have additional vascular controls, which can reduce blood flow to them in times of severe cooling. These controls are mediated through the vasomotor centre in the hindbrain and are autonomic (occur without conscious thought).

Countercurrent heat exchangers

Countercurrent systems are found in many homeostatic systems including in the gills of fish and the kidneys and peripheral circulation of mammals. The operation of these systems depends on the animal's environment. Mammals in cold environments use countercurrent exchange to reduce heat losses to the environment. Those in hot environments may use countercurrent exchange to cool arterial blood supply to the brain during intense activity.



Countercurrent heat exchange systems occur in both aquatic and terrestrial animals as an adaptation to maintaining a stable core temperature. In the flippers and fins of whales and dolphins, and the legs of aquatic birds, they minimise heat loss. For example many birds are able to stand on ice or swim in ice cold water with no negative cooling effects. In some terrestrial animals adapted to hot climates (e.g. gazelles), heat exchangers work in the opposite way to prevent the brain from overheating. Before it flows to the brain, the arterial blood passes (in small arteries) through a pool of cooler venous blood draining from the nasal area where evaporative cooling occurs.

1. Explain why cold adapted terrestrial mammals have regions of the body with thinner fur: ____________________

____

____

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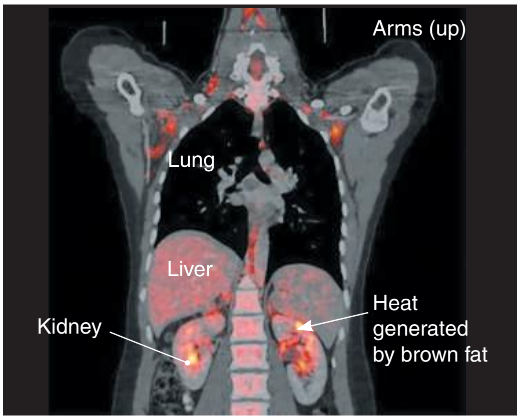
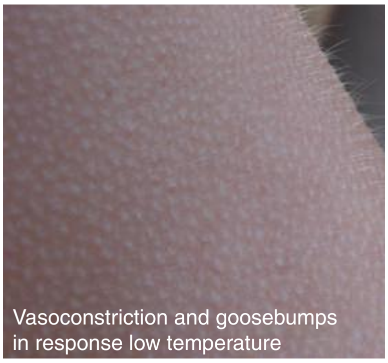


HG6996

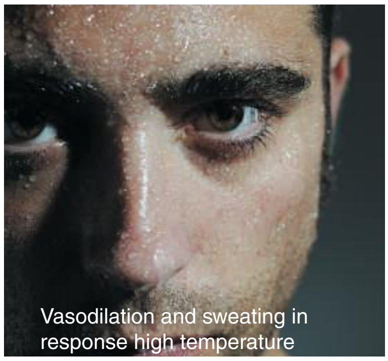
Uncoupling H+ flow and ATP generation

In some cells, such as the brown fat cells of mammals, 'uncoupling' proteins in the inner mitochondrial membrane act as channels, allowing protons to pass directly to the matrix of the mitochondria without being used to generate ATP. This allows the energy of the proton gradient to be dissipated, generating body heat (bright spots above).

Ildar Sagdejev CC 3.0



Vasoconstriction and goosebumps in response low temperature



Vasodilation and sweating in response high temperature

Evaporative heat loss

Evaporative heat loss is a effective way of losing heat. In humans this happens via the production of sweat from sweat glands in the skin. The sweat absorbs heat from the skin which causes it to evaporate. People in warm climates tend to sweat in a more uniform way than those who live in cooler climates. People not acclimatised to warm climates can sweat up to 2 L h^{-1} less than those in warmer climate and the sweat usually beads up and drips off the body.

Not all animals are able to sweat but still carry out evaporative heat loss. Dogs pant, using saliva on the tongue for evaporative cooling. Kangaroos lick their forearms, which have blood vessels close to the surface the skin. Heat is transferred from the skin to the saliva which absorbs the heat and evaporates.

2. (a) Explain how countercurrent heat exchangers help retain body heat in marine mammals: ______________________

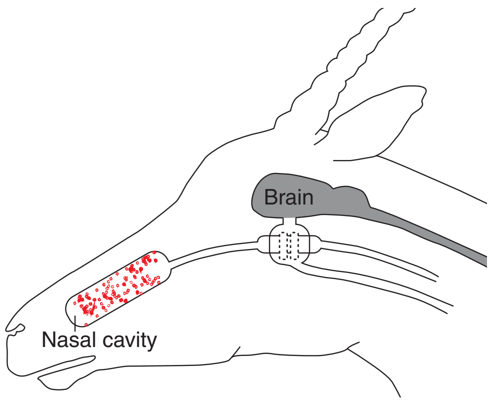
(b) Explain the thermoregulatory changes a marine mammal would make when moving from colder to warmer waters:

3. (a) What is the purpose of sweating and how does it achieve its effect? ______________________

(b) Why does a dab of methanol or ethanol on the skin feels cold, even if the liquid is at room temperature? ___________

4. How do the blood vessels help to regulate the amount of heat lost from the skin and body?

5. The diagram right shows the countercurrent system of blood flow supplying the head of a gazelle. Draw arrows to show the direction of blood flow and label *cooled arterial blood*, *evaporation*, *cool venous blood*, and *warm arterial blood*.



Redrawn from Schnidt-Nielsen, Animal Physiology (1979)

ISBN: 978-1-927309-83-4

152 Hormonal Mechanisms for Thermoregulation

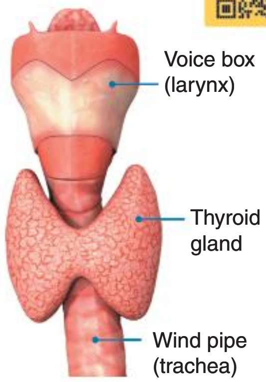
Key Idea: Hormones regulate many aspects of metabolism. Over or under production of hormones can affect metabolic aspects of thermoregulation, as can a lack of cellular response to those hormones.

The hypothalamus has a central role in thermoregulation. It registers changes in core body temperature and coordinates nervous and hormonal responses to restore normal body temperature. Thyroxine, produced by the thyroid gland, is an important hormone in thermoregulation. Insulin also has a thermoregulatory role but this is less well understood.

The thyroid gland and thermoregulation

The thyroid gland is a butterfly shaped endocrine gland located just below the Adam's apple at the front of the trachea. The thyroid secretes several hormones, but the main hormone produced is thyroxine (T_4).

Thyroid hormones have many functions including regulating metabolism, growth and development, and body temperature (below).



Hyperthyroidism and temperature regulation

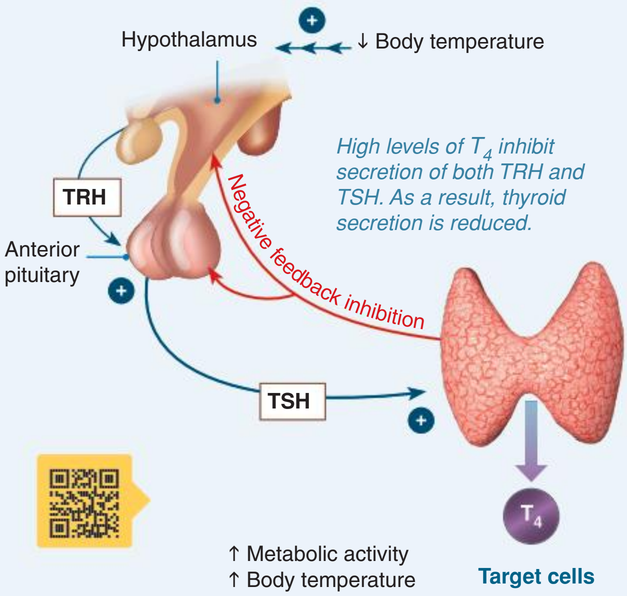
One of the effects of T_4 is to speed up metabolic activity in cells. The increase in metabolic activity also results in the production of heat and, under normal conditions, this is one of the mechanisms by which the body raises body temperature.

The negative feedback regulation of T_4 production can be disrupted by hyperthyroidism, a condition where the thyroid makes too much T_4. This can disrupt temperature regulation.

The most common cause of hyperthyroidism is Graves' disease, characterised by an enlarged thyroid (goiter) and bulging eyes (above). In Graves' disease, the negative feedback loop is bypassed because a protein called thyroid stimulating immunoglobulin (TSI) binds directly to the thyroid and stimulates T_4 production. Because T_4 production is independent of TSH production, the usual regulatory mechanisms are ineffective.

Negative feedback regulates thyroxine production

- Thyroxine (T_4) production is controlled by negative feedback. This mechanism involves two parts of the brain, the hypothalamus and the pituitary gland.
- Low body temperature stimulates the hypothalamus to secrete thyrotropin releasing hormone (TRH), which in turn stimulates cells in the anterior pituitary to secrete thyroid stimulating hormone (TSH).
- TSH acts on the thyroid gland, causing it to produce thyroid hormones, including T_4 (thyroxine). T_4 binds to target cells, increasing their metabolic activity and producing heat.
- High levels of circulating thyroid hormones inhibit production of TRH and TSH. As a result, thyroid secretion is reduced. When the level of thyroid hormones drops below a certain threshold, TRH and TSH production begins again.



1. How is T4 involved in temperature regulation? ______________________________

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2. Explain how T4 production is regulated by negative feedback: ______________________________

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ISBN: 978-1-927309-83-4

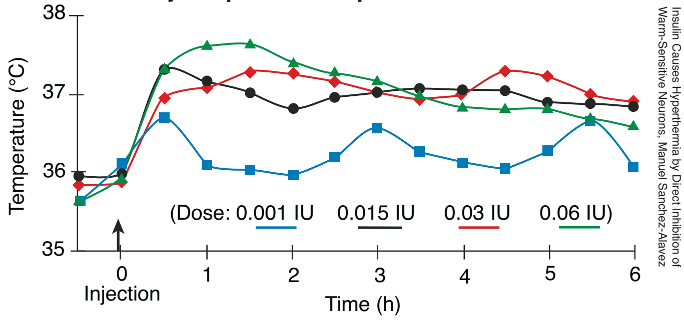
Insulin and thermoregulation

The hormone insulin is normally linked to the regulation of blood glucose. Insulin signals to cells to take up glucose from the blood. The cells then use the glucose to produce ATP for use in metabolic processes. However research has also shown that insulin can directly affect core body temperature.

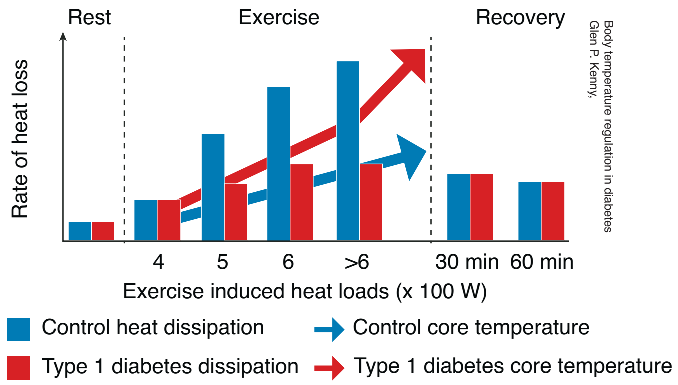
- Experiments have shown that when insulin is injected into the preoptic area of the hypothalamus there is a rapid hyperthermic (increased temperature) response (above right). This was caused by the stimulation of thermogenesis in brown fat (see page 217). This may help to explain why diabetics (whose cells do not produce insulin or do not respond to insulin) often have difficulty with thermoregulation.

- Insulin also indirectly affects thermoregulation. Studies have shown that people with type 1 diabetes (a lack of insulin production) and type 2 diabetes (insulin resistance) often suffer from problems with thermoregulation, including poor control over vasodilation or vasoconstriction. In particular, type 2 diabetes is associated with impaired vasodilation and this can severely affect the ability to dissipate heat. Type 1 and 2 diabetes are also associated with impaired sweat production, which again also affects the ability to dissipate heat.

Body temperature response to insulin in mice



Dissipation of heat and core body temperature



3. Why do high levels of T4 not inhibit its production from the thyroid gland in a person with Graves' disease?

4. (a) Would you expect someone which an overactive thyroid gland to feel hot or cold?

   (b) Would you expect someone which an underactive thyroid gland to feel hot or cold?

5. What was the effect of injecting insulin into the preoptic area of the hypothalamus?

6. (a) Describe how relationship between exercise induced heat loads and core body temperature:

   (b) How does this differ between people with and without type 1 diabetes?

7. Why does impaired vasodilation affect thermoregulation in people with diabetes?

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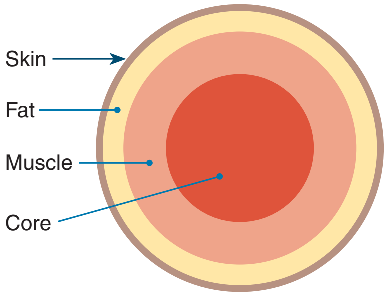
153 Modelling Human Thermoregulation

Key Idea: Modelling heat loss can help us design better clothes and houses, and help develop safer work conditions.

Humans evolved in the warm climate of Africa. As a result, humans are better adapted for dissipating heat than conserving it. For example, we have little body hair, and are generally tall and thin, both adaptations for losing heat. To keep warm, we wear clothes and live in houses, but this can result in us being too hot in some situations (try running a marathon in a polar jacket). By modelling how we thermoregulate we can design clothes and environments that never feel too warm or too cold.



Modelling thermoregulation begins with a simple model of a human in cross section. The model has four layers: the core, muscle, fat, and skin. The model must then account for the rate at which each of these layers produces and dissipates heat. The models become more complicated as different thermoregulatory mechanisms are added (e.g. heat loss by increased blood flow to the skin) and different areas of the body are taken into account (e.g. torso vs legs).

Once a mathematical model for this is produced, we can investigate the effect of changing the environment or adding clothes on the rate of heat loss.

Lauren Pryor

Moisture wicking clothing has become an important part of sports wear. Older fabric trapped sweat, so overheating was a problem. Moisture wicking clothing rapidly moves moisture away from the skin to the outer surface where it is evaporated, leaving a cooler inner surface. Cycling vests are designed to prevent extreme cooling caused by air movement on the front of the torso, but allow for air flow and cooling over the rear of the torso, which is sheltered from the wind.

NASA

Understanding how humans thermoregulate allows us to develop safer working conditions. Working in extremely hot conditions can cause heat stress. Developing clothing that can help regulate body temperature can help this. Astronauts working in space wear body suits through which cool water cycles to regulate their body temperature. Similarly working in extremely cold environments can leave a person at risk of hypothermia.

Many jobs rely on the manual dexterity. Cold fingers make it hard to carry out even simple tasks (imagine zipping up a polar jacket wearing polar grade gloves in a blizzard)! Models of finger skin temperature and dexterity are important in designing gloves and equipment that will provide the best dexterity under a wide range of temperatures and conditions.

The data below shows how dexterity (measured by the number of pins and washers assembled on a Purdue pegboard) changes with skin temperature.

Skin temperature (ST)   Finger dexterity (FD)

ST	FD	ST	FD
7.5	18.5	24	27.5
10	20	25	26
8	20.5	27.5	26.5
10	22	28.5	30
12.5	22	26.5	30
11	23.5	28.5	27.5
15	23.5	11	22
16	24	15	24
12	25	17.5	25
15	26.5	12.5	23
17.5	24.5	25	26
20	26	29	26.5
20	27.5	19	24.5
21	26	10	21

1. Enter the data below left into a spreadsheet (in two columns only). The instructions below are for Microsoft Excel, but most spreadsheets work in a similar way. Select the data and choose to plot a scatter graph. Select one of the data points on the graph and right click to bring up the options menu. Select **Add trendline**. Under **Trendline options** click **Logarithmic**. Under **Forecast** type 10 periods in both **forward** and **backward**. Then click **Display equation on chart**. The equation can be used to calculate dexterity for any point along the graph

   (a) Is there an optimal skin temperature for finger dexterity?

   (b) Why is forecasting the data beyond 40°C not useful?

   (c) How might this kind of data and model be useful for clothing designers and health and safety legislators?

SHE

2

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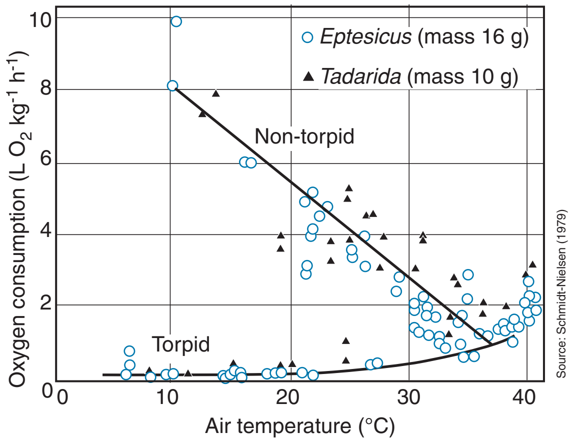
154 KEY TERMS AND IDEAS: Did You Get It?

1. Match each term to its definition, as identified by its preceding letter code.

countercurrent heat exchanger	**A**	An animal that generates its body heat through metabolic activity.
endotherm	**B**	The process that maintains core internal temperature to maintain homeostasis.
hibernation	**C**	A short period of reduced activity and metabolic rate as a strategy to save energy.
thermoregulation	**D**	A prolonged (seasonal) period of reduced activity and metabolic rate.
torpor	**E**	A system of blood vessels in which arterioles and venules are close enough together to transfer heat from one to the other as the blood flows in opposite directions.

2. The plot to the right shows the per mass rate of oxygen consumption in two species of small North American bats. The rate of oxygen consumption is a measure of the energy being used.

   The bats are of similar size, but *Eptesicus* hibernates in the northern part of its range, whereas *Tadarida* migrates south but does not hibernate. With reference to the plot:



   (a) Describe the relationship between air temperature and per mass rate of oxygen consumption in non-torpid bats:

   (b) Why do you think this relationship occurs?

   (c) What happens to the per mass rate of oxygen consumption in bats that enter torpor (relative to that when active)?

   (d) Describe the survival advantage of this behavior to the bats:

3. Polar bears and penguins live in similar polar environments. They have both converged on certain structural features that help them remain warm in polar conditions.

   List three structural features that are similar in polar bears and penguins and describe how these features help them maintain a stable body temperature:

   (a)

   (b)

   (c)

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UNIT 2
Topic 1

Osmoregulation

Key terms

ABA (abscisic acid)
ADH (anti-diuretic hormone)
gills
halophyte
hydrophyte
kidneys
mesophyte
metabolism
osmoconformer
osmoregulation
osmoregulator
osmosis
stomata
urine
xerophyte

Activity number

Principles of osmoregulation

Key skills and knowledge

- ☐ 1 Explain what is meant by osmoregulation and explain why organisms need a specific balance of water and ions in their bodies. **155**
- ☐ 2 Explain the osmoregulatory problems of animals in freshwater, salt water, and on land. Recognise the contrasting difficulties that different environments pose in terms of ion and water fluxes. **155 156**
- ☐ 3 Distinguish between osmoconformers and osmoregulators and explain why all freshwater organisms are osmoregulators. Recall how water and ions enter and leave cells and understand that while osmoregulation carries an energetic cost to the animal it also has benefits. **155**

Peter D. Tillman cc 3.0

Osmoregulatory responses in animals

Key skills and knowledge

- ☐ 4 Identify structural, behavioural, and physiological mechanisms that maintain water balance in animals (osmoregulators and osmoconformers). Know that several mechanisms may be involved in osmoregulation, e.g. the structure of a gill provides the surface across which ions are moved by diffusion or active transport. **155 156**
- ☐ 5 Recognise the close relationship between osmoregulation and excretion and relate this to the organs involved (with reference to fish and mammals in particular). **158 159**
- ☐ 6 Analyse and interpret data related to osmoregulation, e.g. in an intertidal organism. **157**

Structural mechanisms **155 156**

- ☐ 7 Describe and explain structural mechanisms for osmoregulation, including the role of excretory system (kidneys in mammals and kidneys and gills in fish). **158 159**

Behavioural responses **155 156**

- ☐ 8 Describe and explain behavioural responses for osmoregulation including drinking, shade-seeking (to lower evaporative losses), and habitat (salinity) selection.

Physiological mechanisms

- ☐ 9 Using examples, describe and explain physiological mechanisms for osmoregulation including metabolism of glucose and fat, active secretion and reabsorption of ions, concentration of urine, and reabsorption of water from the gut and nasal passages. **158 159**
- ☐ 10 Explain how the hormone ADH regulates urine volume in the mammalian kidney and explain its role in water balance. **160**

Osmoregulatory responses in plants

Key skills and knowledge

- ☐ 11 Describe and explain the main osmoregulatory problem facing most plants. **161**
- ☐ 12 Identify and explain the various mechanisms that maintain water balance in plants of terms of structural features (stomata, vacuoles, cuticle) and hormonal mechanisms (synthesis and action of ABA in response to water stress). Include reference to hydrophytes, mesophytes, xerophytes, and halophytes. **161**
- ☐ 13 **PRAC** Compare the distribution of stomata in plants adapted to different environments. Relate differences to different osmoregulatory challenges. **162**

155 What is Osmoregulation?

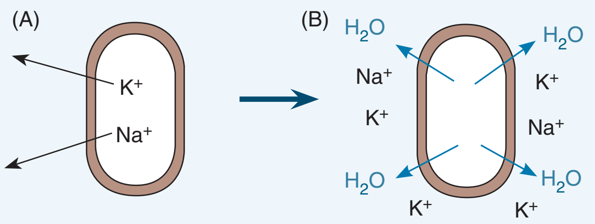
Key Idea: Osmoregulation is the process by which organisms regulate the concentrations of salts and water in their bodies.

The chemical reactions sustaining life require a specific osmotic environment. Organisms in which the osmolarity of the body fluids is different to the osmolarity of the environment must regulate their salt (solute) and water levels through a process called **osmoregulation**. As a result of disease or a change in environment, organisms may sometimes experience **osmotic stress** (an abnormal concentration of dissolved solutes). Osmotic stress disrupts the steady state and can be fatal if the imbalance is prolonged. Osmoregulators are able to maintain the osmolarity of their body fluids independently of the environment. How they do this depends on the type of environment they inhabit.

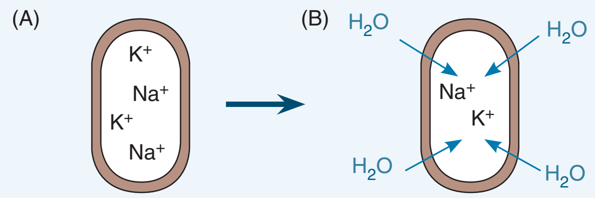
Ion and water fluxes in bacteria

Recall that water will diffuse from regions of lower solute concentration (higher free water concentration) to regions of higher solute concentration (lower free water concentration). Water enters a bacterial cell by osmosis. The bacteria can regulate water fluxes by retaining salts or pumping them out of the cell. They respond to osmotic stress by rapidly accumulating ions or organic solutes via membrane transporters which are stimulated by increases in osmolarity in the environment.

When the solute level is lower outside the cell than inside it, a bacterium will pump salts out of the cell (A) so that water will tend to leave by osmosis (rather than enter (B)).



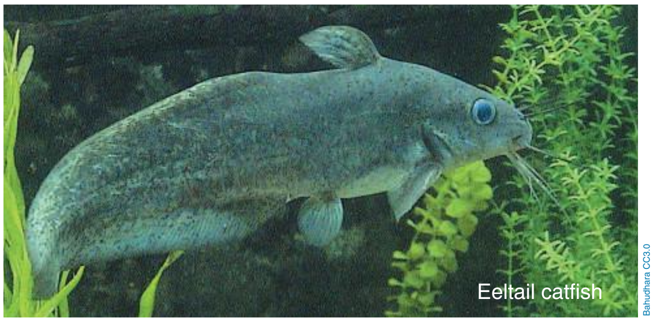
If the solute level is higher outside the cell, a bacterium will retain salts (A), so that water will tend to enter (rather than leave) the cell (B).



Water fluxes in different environments

School of bony marine fish

The type of external environment an organism lives in will dictate the natural direction of water movement. For marine bony fish, the concentration of solutes is higher in the environment than in the body fluids of the fish. The fish loses water across the skin and gills, and it must be replaced or the fish will experience osmotic stress.



Eeltail catfish

The body fluids of freshwater fish contains a higher solute concentration than the fresh water environment. The fish gains water as it flows across the gills during gas exchange. A freshwater fish must remove the excess water from its body or it will experience osmotic stress.

1. What is osmoregulation? ____________________

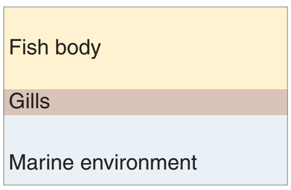
2. How does the bacterium reduce the amount of water entering the cell? ____________________

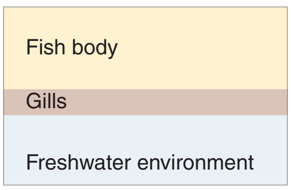
3. The two diagrams (right) depict a bony fish in a marine environment and a bony fish in a freshwater environment.

   (a) On each diagram, draw arrows to show the direction of water movement:

   (b) In the marine environment, the fish body is hypertonic / hypotonic to the seawater (delete one)

   In the freshwater environment, the fish body is hypertonic / hypotonic to the water (delete one)





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156 Osmoconformers and Osmoregulators

Key Idea: Osmoconformers match the osmolarity of their environment. Osmoregulators tightly regulate their salt and water balance. All freshwater organisms are osmoregulators.

Organisms have differing abilities to respond to environmental change. Osmoconformers match the osmolarity of their environments and do not regulate their water and ion fluxes. In contrast, osmoregulators maintain relatively constant water and ion concentrations independently of the environment.

Osmoconformers

Not all organisms osmoregulate. Those that do not are called **osmoconformers**. In osmoconformers, the osmolarity of the body fluids (number of solute particles per litre) fluctuates with the osmolarity of the environment. However, the solute composition of body fluids may be different to those in the water.

All osmoconformers are marine (although not all marine organisms are osmoconformers)! Most marine invertebrates are osmoconformers and many rely on a relatively stable external osmotic environment for survival. Deviations outside of their tolerance range are fatal. However, some intertidal species can tolerate greater fluctuations in the osmotic environment, such as occur with the frequent dilutions of seawater as the tide changes.

Osmoregulators

Animals that regulate their salt and water fluxes independently of the environment, such as bony fish and marine mammals, are osmoregulators. Osmoregulation requires large amounts of energy. Marine bony fish lose water osmotically and counter the loss by drinking salt water and excreting the excess salt across the gill surfaces. Marine mammals produce a urine that is high in both salt and urea.

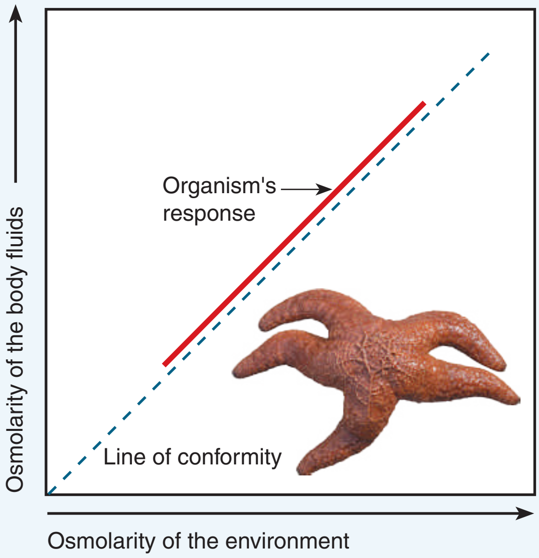
Freshwater animals, such as the freshwater crayfish (yabby), above right, have body fluids that are osmotically more concentrated than the water they live in and all are osmoregulators. Water tends to enter their tissues by osmosis and must be expelled to avoid flooding the body. Freshwater crayfish osmoregulate by excreting the excess water.

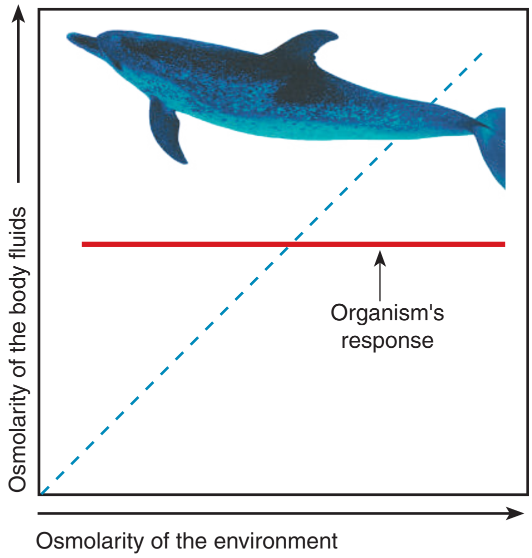

Anemone


Crayfish


Marine bony fish


Yabby





1. (a) Use the graphs above to explain how osmoconformers differ from osmoregulators: ______

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Sharks are a special case of osmoconformers

Marine sharks are special case of osmoconformers. They are osmoconformers, but ion regulators, and generate osmotic concentrations in their body fluids similar to seawater by tolerating high urea and absorbing seawater directly. Excess salt from the diet is excreted via a salt gland in the rectum.

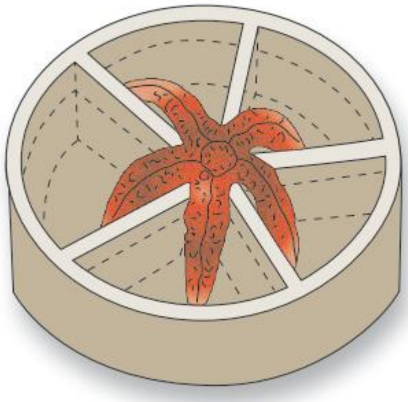
Osmoconformers don't need to expend as much energy as osmoregulators in order to regulate ion gradients but a small amount of energy is still expended on ion transport in order to maintain the correct ion balances for normal metabolic function.

Sharks tolerate high tissue urea

Responding to salinity

The common sea star (*Asterias rubens*) is found throughout the Atlantic. It can be found at a wide range of depths of 0-400 m and must contend with large variations in temperature and salinity. It tolerates a wide range of salinity, but above a certain level development, reproduction, and survival are negatively affected.

Sea stars are mobile and will move to find suitable environmental conditions. This behavioural response puts takes them away from a potentially harmful environment and places them in a more favourable one. This is shown in the experiment below where scientists exposed sea stars to a range of salinities (amount of dissolved salt in parts per thousand) within a five-compartment chamber. The animal was placed in the centre of the chamber with each arm experiencing water of different salinity. The animal then crawled into the compartment with the preferred salinity.



Left: Sea star choice chamber. Each compartment contains water of a different salinity.

(b) Describe one advantage and one disadvantage of being an osmoconformer:

2. (a) Why are sharks considered to be a special type of osmoconformer?

(b) Sharks expend some energy to maintain a specific ion balance. Why is it important the balance is maintained?

3. Why do you think all freshwater organisms are osmoregulators?

4. Devise an experiment to show how the salinity choice chamber could be used to determine the preferred salinity of a sea star. Write you method in bullet points below:

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157 Osmoregulation in Intertidal Organisms

Key Idea: A line of best fit or a linear regression can be used to determine if there is a relationship between an organism's ability to regulate salt and water levels in different concentrations of saltwater.

Intertidal species are subjected to varying levels of salinity as the tides come in and out and sea water mixes with freshwater. Species of intertidal crabs vary widely in their ability to regulate their salt and water levels in the face of environmental fluctuations. A student investigated the effect of increasing seawater dilution on the cumulative weight gain of a common rock crab. The methodology and results are provided below.

The aim

To determine the effect of seawater concentration on crab weight gain.

The method and results

- Six common rock crabs were used in the experiment.
- Three were placed in seawater dilution of 75:25 (75% seawater) and three were placed in a seawater dilution of 50:50 (50% seawater).
- Cumulative weight gain (mg) in each of the six crabs was measured at 3 minute intervals over a period of 30 minutes.

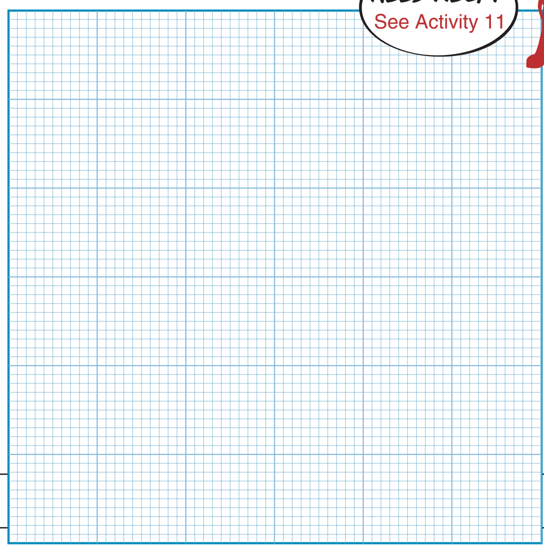
The results

The results are presented in the table (right).

Table 1. Cumulative weight gain in crabs at two seawater concentrations

	Cumulative weight gain (mg) in 75% seawater			Cumulative weight gain (mg) in 50% seawater		
Time (min)	**Crab 1**	**Crab 2**	**Crab 3**	**Crab 1**	**Crab 2**	**Crab 3**
3	3.8	4.0	4.0	5.6	6.2	5.8
6	8.0	8.3	7.7	11.2	11.6	11.9
9	11.5	11.0	9.5	17.0	17.6	17.2
12	14.8	15.1	15.2	23.5	23.6	24.0
15	18.9	19.5	19.7	29.0	28.2	28.6
18	23.5	22.9	23.8	33.0	32.5	32.7
21	26.5	26.9	26.7	37.5	37.6	39.0
24	31.5	32.0	31.2	43.1	43.5	43.6
27	35.0	35.5	35.5	48.0	48.1	47.5
30	40.0	40.1	41.2	53.0	52.6	52.8

1. Plot the raw data for each individual crab for each seawater concentration as two scatter plots on the grid. Use different colours to distinguish the data sets.



2. Evaluate the strength of the relationship between the concentration of seawater and crab weight gain. You can do this in two ways:

   (a) Draw a line of best fit for the data at each seawater concentration.

   (b) Enter the data on a spreadsheet (time vs weight gain for each seawater concentration). Plot the data and fit a regression line for each data set. Show the regression equation and the R^2. Print the graph and attach it here.

   (c) How well does your chosen method fit the data?

   ____

   (d) Why does a regression provide more information? ____

3. (a) Explain what is happening at each seawater concentration: ____

   (b) What does this experiment suggest about the osmoregulatory ability of this crab species? ____

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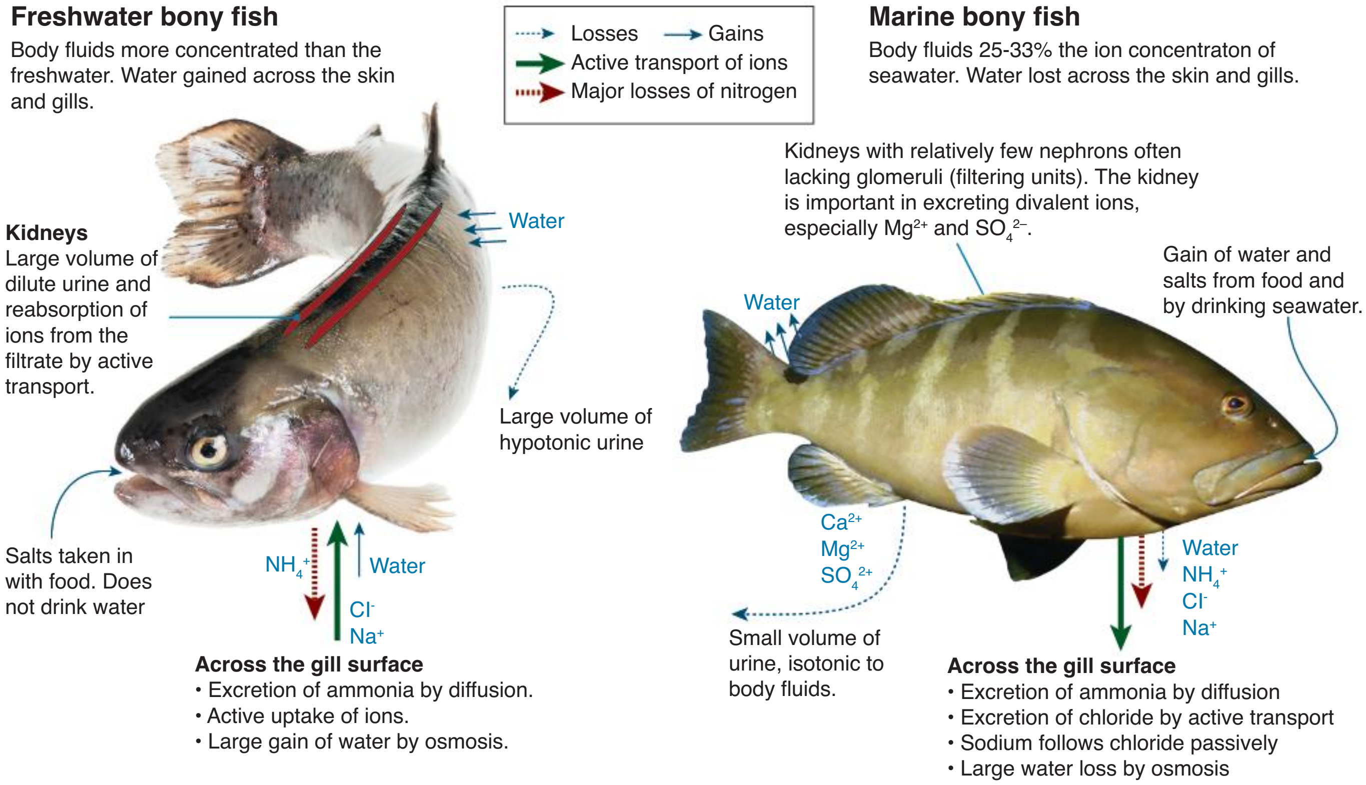
158 Osmoregulation in Bony Fish

Key Idea: Gills are the primary organs for osmoregulation in fish, which must balance water and ion fluxes.

Bony fish face contrasting osmoregulatory problems depending on their environment. In fish, osmoregulation and excretion of ions and nitrogenous wastes are closely linked. Fish kidneys are unable produce a urine that is more concentrated than the body fluids and nearly all their nitrogenous waste is excreted via diffusion across the gills, which also have an important role in salt balance. In freshwater fish, excess water is lost in copious amounts of dilute urine. In marine fish, the kidneys produce a scanty urine with the same osmolarity as the blood.



Freshwater fish gain water by osmosis so must excrete this excess water as well as nitrogenous waste. Their kidneys produce large volumes of dilute urine, which results in loss of valuable ions. To compensate, the kidneys reabsorb salts from the filtrate and the gills take up ions from the water.

Marine fish lose water to the environment by osmosis and must drink to replace this lost fluid. They extra salts they take in with drinking are excreted by active transport across the gill surfaces. Fish cannot concentrate the urine so the urine is isotonic and scanty. Ammonia lis lost by diffusion across the gills.

1. Describe the contrasting problems of excretion and osmoregulation for bony fish in fresh and salt water environments:

____

____

____

2. (a) Explain why marine bony fish must drink vast quantities of salt water: _______________________

____

____

(b) Explain why freshwater fish do not drink water at all: _______________________

____

____

3. (a) How are the gills involved in osmoregulation in a freshwater fish? _______________________

____

(b) How are the gills involved in osmoregulation in a marine bony fish? _______________________

____

ISBN: 978-1-927309-83-4

159 Managing Fluid Balance on Land

Key Idea: Terrestrial animals have adaptations to obtain enough water to maintain their fluid and ion balance, either through drinking or the metabolism of foodstuffs.

All organisms, whether terrestrial or aquatic, must maintain their water and solute concentrations at levels that support their life processes. For animals on land, the main challenges to fluid and ion regulation arise from a dependence on water, which is often in short supply. The water an animal loses must be replaced by an equal volume. These fluxes make up the animal's water budget. Water losses though evaporation from the skin and lungs, and in urine and faeces are balanced by water gains through eating and drinking. Animals show specific adaptations for obtaining and conserving water in an environment where water loss is a constant problem.

Obtaining water

Most animals obtain the majority of their water by drinking. Some, such as the emu, drink infrequently, but when they do drink they consume a large volume of water. For many large predators (e.g. lions) living in dry environments, obtaining water from the food they eat is an important source of water.

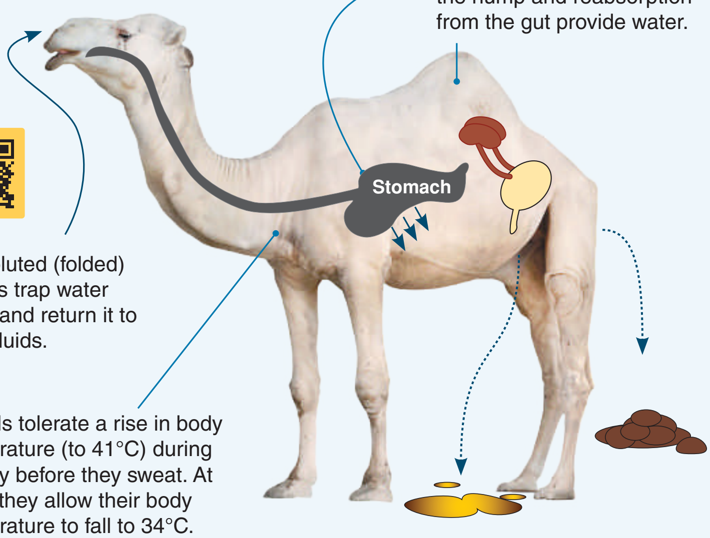
Many of Australia's arid-adapted marsupials, e.g. the bettong and many of the macropods, have low water requirements and rarely drink, obtaining much of their water from oxidation of dry foods (producing ATP, CO_2, and water). The rest comes from the small amount of water present in the food.

Amphibians can take up water directly through the skin, which is water permeable. When they need water, they can acquire it by osmosis while submerged or resting on a damp surface. Desert adapted frogs burrow underground and spread wax over their skin from epidermal wax glands.

Conserving and losing water in camels

All mammals excrete nitrogenous wastes as urea and lose water through urine, faeces, and evaporative losses from the skin and lungs. Arid-adapted mammals all show similar adaptations to their dry environment. All have long loops of Henle in the kidney and produce a very concentrated urine. Many have reduced sweat glands to conserve water in dry environments.

Camels have further adaptations for life in desert conditions, most directly related to water balance. For example, camels (being ruminants) can retain relatively large volumes of water in the gut, but most will need to regularly visit a water supply. When they have access to water, a dehydrated camel can drink up to 200 L in 3 minutes. In most animals, this would cause osmotic shock, but the camel's red blood cells can withstand huge fluctuations in body water content.



1. Name four ways in which water can be obtained: ______________________________

____

____

2. How does metabolism provide water for the body's activities? ______________________________

____

____

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General adaptations associated with major routes of water loss in animals (vertebrates and arthropods)	
An insulated body covering	Body coverings reduce but do not totally eliminate water loss. They form a moderate barrier against water loss and may be thickened or covered with insulation or wax to limit water loss.
Using metabolic water	All animals produce water through metabolism. Metabolising fat yields more water than metabolising carbohydrate and this can be used to maintain water balance when no liquid water is available.
Changing behaviour	Behavioural strategies to reduce water losses, such as seeking shade, are common and may be associated with physiological adaptations to take up water from humid environment.
Minimising losses from the excretory system	Water balance and excretion are tightly linked because excretion of nitrogenous wastes represents a major route for water loss. Being able to produce a concentrated urine is a feature of terrestrial life.

Saleem Hameed cc 2.5

Arthropods

DannyS cc 3.0

Reptiles

Birds

The permeability of the waxy cuticle of desert adapted arthropods is very low, greatly reducing water loss across the body surface. Insects excrete nitrogenous wastes as uric acid with low water loss, and many are able to take up water from the air when humidity increases. Desert darkling beetles (above) can collect water on their hardened forewings.

Birds and reptiles share many strategies for water conservation (a reflection of their shared ancestry). Scales in reptiles and feathers in birds (which are modified scales) reduce water losses from the body surface. Neither sweats and although water is lost in breathing, excretion of nitrogen as uric acid results in minimal loss of water. Marine birds and reptiles also have salt glands to excrete excess salts gained from eating and drinking. Shade-seeking behaviour reduces water losses during the day. In omnivorous birds (e.g. emus) reabsorption of water from food is a major source of water. Desert reptiles, such as goannas, obtain most of their water from their food and some can also absorb water across the nasal epithelium.

3. Identify three ways in which animals lose water to the environment: ______________________

____

____

4. What features of fluid and ion homeostasis do reptiles and birds share? ______________________

____

____

5. Identify two ways in which each of the following animals conserves water:

(a) Arthropod: ______________________

(b) Amphibian: ______________________

(c) Reptile: ______________________

(d) Bird: ______________________

(e) Mammal: ______________________

6. In humans, water intake generally equals water losses over the course of a day. During a 24 hour period a student obtained 2500 mL of water from eating, drinking, and metabolism. They produced 1500 mL of urine in the same period.

(a) Calculate the percentage of total water gains lost as urine: ______________________

(b) Suggest how the remaining water is lost: ______________________

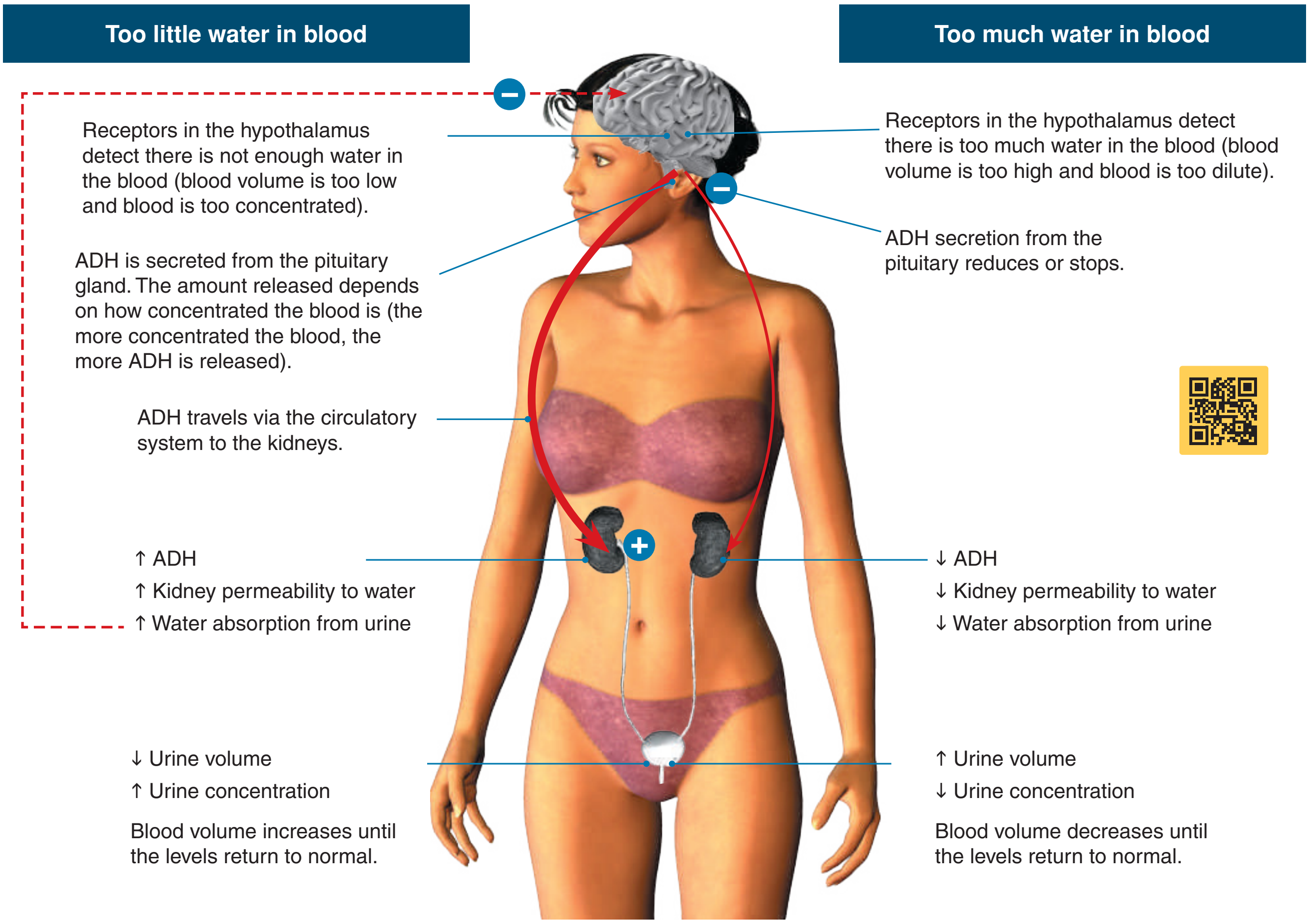
____

ISBN: 978-1-927309-83-4

160 ADH and Water Balance

Key Idea: Antidiuretic hormone (ADH) helps maintain water balance by regulating water absorption by the kidneys.

The body regulates water balance in response to fluctuations in fluid gains and losses. One mechanism by which fluid balance is maintained is by varying the volume of water absorbed by the kidneys and thereby the concentration of the urine produced. This involves a hormone called **antidiuretic hormone** (ADH). Osmoreceptors in the hypothalamus monitor blood osmolarity (solute content) and send messages to the pituitary gland which regulates the amount of ADH released. ADH promotes the reabsorption of water from the kidney collecting ducts, producing a less or more concentrated urine.



1. What effect does ADH have on the kidneys? ______________________________

____

____

2. How do negative feedback mechanisms operate to regulate blood volume and urine output? ______________________________

____

____

____

3. Predict whether a high fluid intake would increase or decrease ADH production: ______________________________

4. (a) Diabetes insipidus is a type of diabetes caused by the lack of ADH. Based on what you know about the role of ADH in kidney function, describe the symptoms of this disease:

____

____

(b) How would diabetes insipidus be treated? ______________________________

____

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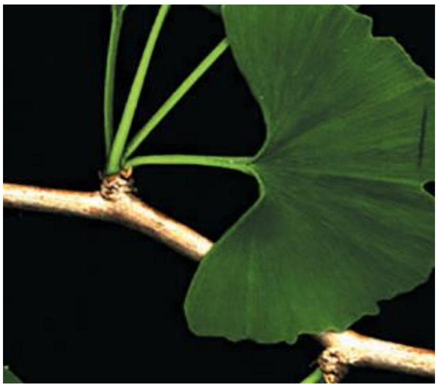
161 Osmoregulation in Plants

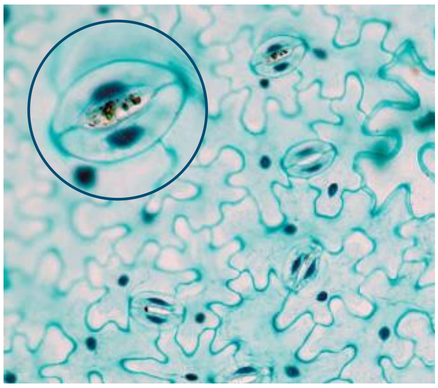
Key Idea: Plants in a range of habitats show a variety of adaptations for maintaining water balance.

Most plants are mesophytes. These are plants which are adapted to grow in average conditions (moderate to warm, humid environments). Water loss is not usually a problem for them so they have no adaptations associated with surviving in extreme conditions. In contrast, plants growing in extreme environments (aquatic, semi-aquatic, dry, or salty environments) have adaptations to survive these conditions. Many of their adaptations help to minimise water loss.

Generalised features of mesophytes


Tasmanian rainforest


WBS



The generalised features of mesophytes allow them grow well in moderate environments. They generally have large root masses, which provide a large area for obtaining water. Large water uptakes compensate for the water lost through the stomata when they are open during the day. In plants, water loss is an inevitable consequence of gas exchange.

Leaves are broad and thin with a waxy cuticle that covers the epidermis and limits evaporation from the leaf surface. Recall that stomata allow CO_2 to enter the leaf but this also allows water to escape. Mesophytes tend to have more stomata on the leaf undersides, which reduces water loss via transpiration without restricting the entry of CO_2.

Recall that turgor changes in the guard cells open and close the stomata to regulate water losses. The hormone abscisic acid (ABA) is synthesised in response to water stress and regulates stomatal closure. When water is low, ABA levels increase and K^+ and Cl^- leave the guard cells. Water follows by osmosis and the guard cells flop together, closing the pore.

Leaf and root structure of hydrophytes

- Hydrophytes are plants adapted to aquatic or semi-aquatic environments. Because of their watery environment they do not need to prevent water loss.
- The stomata are present in high numbers on the upper surface of the leaf only. The waxy cuticle on the leaf is designed to repel water off the leaf rather than to prevent drying out.
- The emergent leaves of hydrophytes are broad to increase the area for photosynthesis and also to aid flotation. Submerged leaves tend to be thin and divided. Any water lost from their broad surface by transpiration or evaporation is easily replaced.
- The root system of hydrophytes is much smaller than those of mesophytes. This is because its main function is to anchor the plant rather than a dual role of also obtaining water from the soil.

1. Explain why mesophytes do not show many adaptations for preventing water loss: ______

2. Compare the differences in leaf and root structure between hydrophytes and mesophytes and explain the reason for the differences:

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Adaptations of xerophytes

Plants adapted to dry conditions are called xerophytes. Most xerophytes are found in deserts and semi-arid areas, but they may be found in humid environments, provided that their roots are in dry micro-environments (e.g. the roots of epiphytic plants that grow on tree trunks or branches).

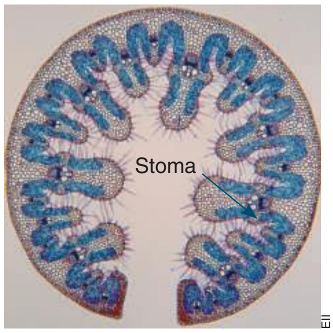
- Xerophytes, such as cacti and Australia's sclerophyll plants, have a number of adaptations (called xeromorphic adaptations) that allow them to conserve water and survive in dry environments. These adaptations include small, hard leaves (sclerophylls), an epidermis with a thick cuticle, sunken stomata, succulence, and permanent or temporary absence of leaves.
- Many xerophytes have a succulent morphology. Their stems are often thickened and retain a large amount of water in the tissues, e.g. aloe.
- Many xerophytes have a low surface area to volume ratio, reducing the amount of water lost through transpiration.

Acacia trees have deep root systems, which allows them to draw water from sources deep underground.

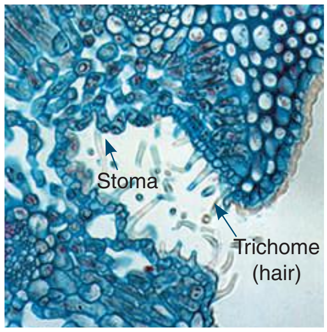
An outer surface coated in fine hairs traps air close to the surface and reduces transpiration.

Adaptations in cacti

Desert plants, such as cacti (below), must cope with low or sporadic rainfall and high transpiration rates.



Coastal grasses, e.g. marram grass (above), have curled leaves. Stomata are sunken in pits, creating a moist microclimate around the pore, which reduces transpiration rate.



Oleander has a thick multi-layered epidermis and the stomata are sunken in trichome-filled pits on the leaf underside which restrict water loss.

3. What is a xeromorphic adaptation? ______________________________

____

4. Describe three xeromorphic adaptations of plants that reduce water loss:

(a) ______________________________

(b) ______________________________

(c) ______________________________

5. How do sunken stomata reduce water losses via transpiration? ______________________________

____

____

6. How does a low surface area to volume ratio in a plant such as a cactus reduce water loss? ______________________________

____

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Adaptations of halophytes

Halophytes are plants adapted to growing in saline (salty) environments. Mangroves are halophytes and show many of their typical adaptations. They are shrubs or small trees and grow in water-logged substrates in estuarine environments. Not only is their growth environment high in salt, but the salinity level fluctuates with tidal flows. Evaporation of water at low tide can greatly increase the salt levels compared to when the tide is in.

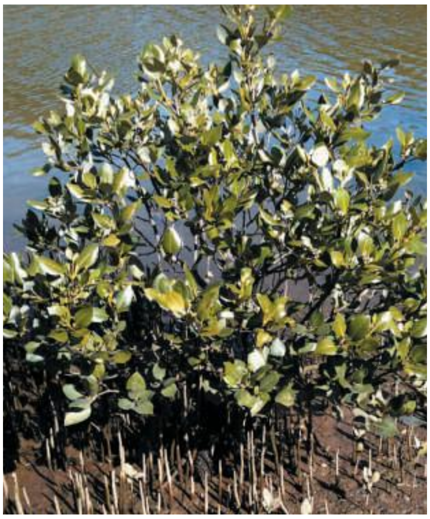
The high salt environment would kill most other kinds of plants because high extracellular salt levels cause water to leave the cells. Mangroves overcome this by storing salt in their cell vacuoles and maintaining a high concentration of solutes in the cell cytoplasm. This reverses the osmotic gradient and maintains the transpiration stream.

Australia has 45 species of mangroves. They are found in a range of habitats including tropical, subtropical, and sheltered temperate coastal rivers, as well as estuaries, bays, and marine shorelines. They grow in the upper part of the intertidal zone, but may extend further inland to form salt marshes and coastal wetland communities. Almost half of Australia's mangrove forests are located in Queensland.

BoundaryRider cc 3.0

RA

Mangroves have specialised "breathing roots" called pneumatophores. They protrude above the surface of the mud and allow the mangrove to obtain oxygen even when the tide is in. A waxy coating of suberin on the root cells excludes 97% of salt from the water taken up by the roots.



RA

Mangrove leaves are adapted for conserving water. They are covered in a thick waxy cuticle or dense hairs to reduce water loss. Sunken stomata limit water loss via transpiration. Leaves may also store water or orientated to minimise water loss in the hottest part of the day.

Some species of mangroves can secrete salt through salt glands in the surface layer of the leaves. This active transport process requires energy expenditure. Other mangrove species store salt in older leaves before they fall from the tree, taking the salt with them.

7. Describe a physiological problem associated with living in a high salt environment: ______________________________

8. Describe three methods by which various mangrove species solve the problem of a high salt environment:

(a) ______________________________

(b) ______________________________

(c) ______________________________

ISBN: 978-1-927309-83-4

162 Investigating Stomatal Density

Key Idea: The density and distribution of leaf stomata in different plant species are related to the rate of water loss.

Different plant species have different leaf shapes and structures and these can be correlated with the environment in which they are found. Comparing the leaf area and stomatal density of different plant species helps to explain observed differences in transpiration rate but factors in the environment, such as shading and wind, are also important.

Plant species show different leaf shapes and structures associated with their environments

Aloe (agave)
A succulent

Tropical species with thick, fleshy leaves. Physiology allows it to fix CO_2 during the night and keep stomata closed during the day.

Pine
A conifer

Temperate species with thin, needle like leaves and a thick waxy leaf cuticle. Stomata are sunken into pits.

Eucalyptus
An Australian gum tree

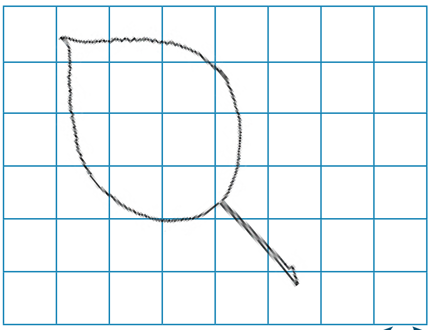
Sub-tropical drought tolerant species with a deep root systems and waxy leaves that hang downwards.

Sunflower
A perennial dicot with large leaves

Widespread cultivated North American dicot with a showy flower head and very large soft leaves.

Measuring leaf area

Leaf area can be measured by tracing the leaves onto graph paper and counting the squares, or by tracing or photocopying the leaves onto a paper of a known mass per area, then cutting out the shapes and weighing them. For both methods, multiply by 2 for both leaf surfaces.

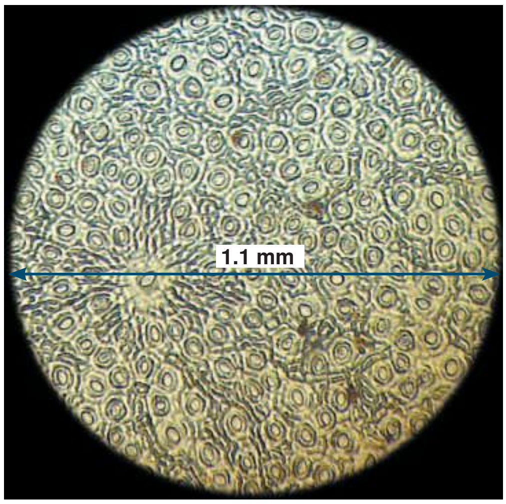


Calculating SA by mass:
Photocopying leaves onto paper with a known gsm (grams per square metre) allows you to calculate the surface area from the mass of paper they cover.

Calculating SA by leaf trace method:
Count entire squares covered by the leaf. Estimate the area of the partial squares by counting those that are at least half covered by the leaf and disregarding those that are less than half covered.

Determining the number of stomata per mm^2

The number of stomata per mm^2 on the surface of a leaf can be determined by counting the stomata visible under a microscope. Painting clear nail polish over the surface of a leaf and leaving it to dry creates a layer with impressions of the leaf surface. This can be peeled off and viewed under the microscope to count stomata (below).



1. (a) Determine the area of the leaf traced onto the blue grid above: ______________________

   (b) Twenty leaves from plant A were taped to paper and photocopied on to 80 gsm paper. The shapes were cut out and weighed on a digital balance. The total weight of shapes was 3.21 grams. Calculate the surface area of the leaves.

   ____

2. Calculate the number of stomata per square millimetre in the microscope view of the leaf above: ______________________

   ____

56 119

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The aim

To evaluate the relationship between transpiration rate and stomatal density by examining a variety of plant species.

Background

Plants lose water all the time by evaporation from the leaves and stem. This loss, mostly through pores in the leaf surfaces, is called **transpiration**. Despite the adaptations of plants to reduce water loss (e.g. waxy leaf cuticle), 99% of the water a plant absorbs from the soil is lost by evaporation. Different species of plant are adapted to different physical conditions. These conditions may affect the number of stomata per mm^2 of leaf and the transpiration rate of the plant.

The method

Six plant species from a range of habitats were chosen for use. The stems of several specimens of each species were cut while submerged and set up in a potometer similar to that described earlier but with a larger capacity. The temperature was measured at 21°C. The plants were left to transpire in still air at 70% relative humidity for 2 hours and the volume of water transpired was recorded. The surface area of the leaves was also determined as was the number of stomata per mm^2.

3. Write a hypothesis for the investigation: ______________________________

____

Table 1: Water loss in various plant species over 2 hours

	Total leaf area (cm^2)	Total water lost (µL)	Transpiration rate (µL cm^{-2} h^{-1})	Number of stomata per mm^2 upper surface	Number of stomata per mm^2 lower surface	Total number of stomata per mm^2
Sunflower: *Helianthus annus*	2000	6081		71	172	
Busy Lizzie: *Impatiens sultani*	620	3017		29	143	
Geranium: *Pelargonium zonale*	3800	3721		19	52	
Garden bean: *Phaseolus vulgaris*	1340	4147		40	250	
Caster oil plant: *Ricinus communis*	860	3609		52	121	
Corn: *Zea mays*	4100	6402		60	101	

4. Complete the table by calculating the transpiration rate and total number of stomata per mm^2 for each plant in table 1:

5. (a) Which plant has the highest transpiration rate? ______________________________

   (b) Which plant has the lowest transpiration rate? ______________________________

6. (a) Which plant has the highest stomatal density? ______________________________

   (b) Which plant has the lowest stomatal density? ______________________________

7. (a) Is there a relationship between the number of stomata per mm^2 and the transpiration rate?

   ____

   ____

   (b) Explain your answer: ______________________________

   ____

   ____

   ____

8. (a) Where are the majority of stomata located In a typical dicot leaf? ______________________________

   (b) Suggest why this might be the case: ______________________________

   ____

   ____

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163 KEY TERMS AND IDEAS: Did You Get It?

1. The following examples give ways in which organisms osmoregulate. Decide whether they are examples of structural (morphological), behavioural or physiological adaptations:

(a) The secretion of ADH in response to low blood volume: ___

(b) The stomata on xerophyte leaves are sunken: ___

(c) A freshwater fish takes up ions across the gill surface: ___

(d) The roots of mangrove trees are covered in a waxy substance to prevent salt uptake: ___

(e) Camels metabolise stored fat in their hump to produce water: ___

(f) A goanna seeks shade during the hottest part of the day: ___

(g) Secretion of salt from salt glands in a mangrove: ___

2. Define the following terms:

(a) Mesophyte: ___

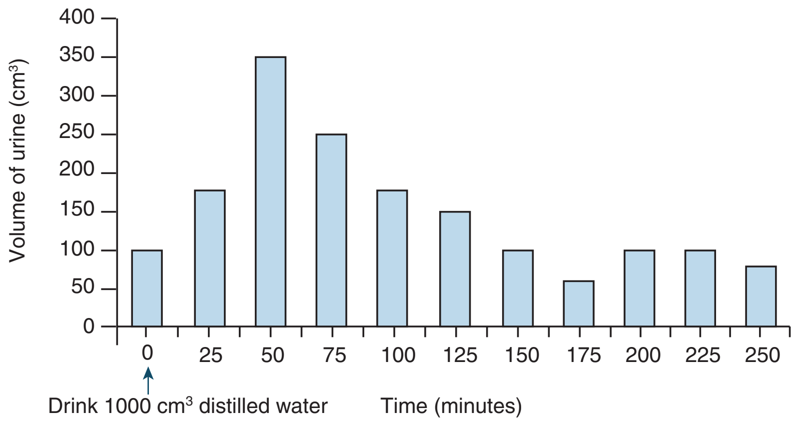
(b) Xerophyte: ___

(c) Hydrophyte: ___

(d) Halophyte: ___

3. The graph below shows the volume of urine collected from a subject after drinking 1000 cm^3 of distilled water. The subject's urine was collected at 25 minute intervals over a number of hours.

(a) Explain the difference in the volume of urine collected at 25 minutes and 50 minutes:



(b) Explain how ADH production, urine concentration and production, and kidney permeability would be affected by drinking 1000 cm^3 of water:

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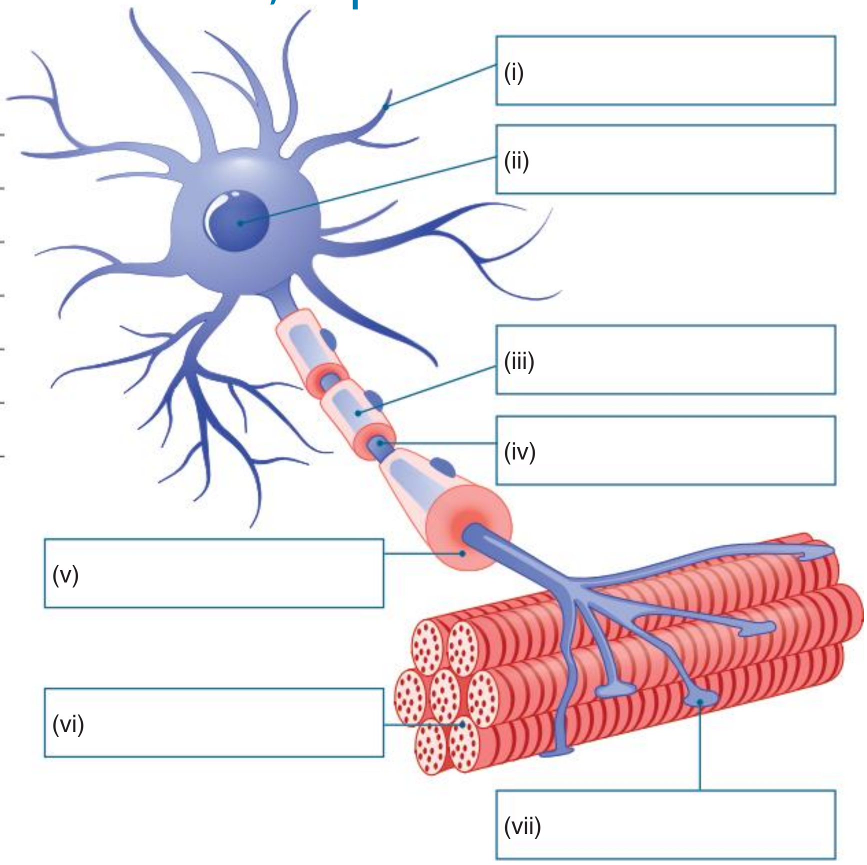
164 Synoptic Question: Unit 2, Topic 1

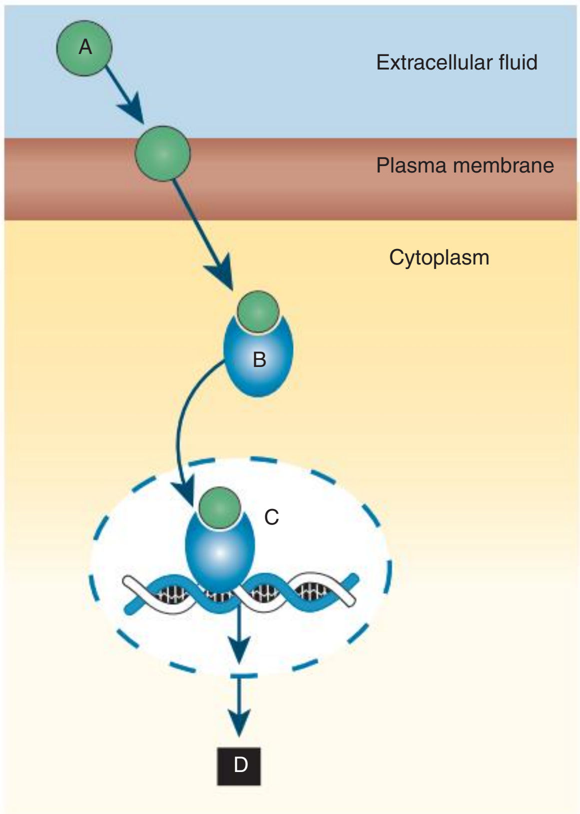
1. (a) What type of neurone is shown in the diagram right? Justify your answer:



(b) Use the following word list to label the diagram: *Soma (cell body), myelin sheath, node of Ranvier, muscle fibre, axon, dendrites, synaptic knob*.

(c) Draw an arrow on the diagram to show the direction a nerve impulse would travel along this neurone:

2. Cells use chemical messengers to communicate and to respond to their environment. The diagram below shows a form of cell signalling.



(a) Describe the basis of cell signalling in terms of a receptor, cell signalling molecule, and a target cell:

(b) Why is it important that not all cells respond to every cell signal?

(c) On the diagram, what type of signal molecule is A? Explain your reasoning:

(d) What is the structure labelled B?

(e) What role is structure B playing at point C on the diagram?

(f) What is the result of this pathway at point D?

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3. (a) Using thermoregulation as an example, explain why maintaining homeostasis is crucial for ensuring metabolic reactions can proceed?

(b) Humans lose almost half of their body heat through the head. Suggest a behavioural and a structural adaptation that could reduce this loss:

(c) An experiment was performed with three volunteers with the same body shape and dimensions. Volunteer A was given good insulated clothing, including an insulated knit hat, volunteer B was also given well insulated clothing but no insulated hat, volunteer C wore only a light shirt and pants. The three stood in a freezer room (-18°C) for five minutes while their core body temperature was monitored.

Explain what will happen to the body temperature of these three volunteers and explain why:

4. Mesophytes have few adaptations to restrict water losses whereas plants living in arid or saline environments have many adaptations to conserve water. Explain how adaptations in xerophytes and halophytes help regulate water balance:

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UNIT 2
Topic 2

Infectious Disease

Key terms

antibiotic
antimicrobial
bacterial disease
bactericidal
bacteriostatic
cellular pathogen
fungal disease
infectious disease
Koch
non-cellular pathogen
non-infectious disease
pathogen
pathogenesis
prion
protist
protozoan disease
Semmelweis
vector
viral disease
virulence factor

Activity number

Pathogens and disease

Key skills and knowledge

- ☐ 1 Understand what is meant by disease. Distinguish between infectious diseases and non-infectious diseases and give examples. **165**
- ☐ 2 Describe the nature of pathogens and explain their role in infectious disease. Identify types of pathogens, including viruses, prions, bacteria, fungi, protists and parasites by their characteristics. **165**
- ☐ 3 Explain what is meant by pathogenesis. Identify and describe virulence factors (factors produced by pathogen that add to their effectiveness) including adherence factors, invasion factors, capsules, toxins, and life cycle changes. **166-171**
- ☐ 4 In more detail than above, describe features of the different types of pathogens (#5-9 below), including relevant virulence factors and adaptations specific to the pathogen involved.
- ☐ 5 Bacterial pathogens: Diseases include tuberculosis, cholera, tetanus, *Salmonella* poisoning, and crown gall in plants. **166**
- ☐ 6 Fungal pathogens: Diseases include amphibian chytrid fungus disease. **167**
- ☐ 7 Protistan pathogens: Diseases include malaria (protozoan) and *Phytophthora* dieback (oomycetes or water moulds, not to be confused with fungal moulds). **168**
- ☐ 8 Viral pathogens: Diseases include HIV/AIDS, influenza, Ross River virus, measles, and Ebola. **169 170**
- ☐ 9 Prion pathogens: Diseases include variant Creutzfeldt–Jakob disease (vCJD), kuru, BSE, and scrapie. **171**
- ☐ 10 **SHE** Explore the historical understanding our understanding of disease and its transmission, including the work of Koch and Semmelweis. **165**


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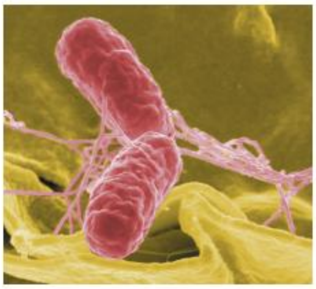

NIH

Transmission of disease

Key skills and knowledge

- ☐ 11 Describe modes of disease transmission to include transmission by direct contact, by contact with body fluids (e.g. blood or saliva), by contaminated food or water, and via vectors (e.g. insect vectors). Identify mode of transmission from given data. **165 172**
- ☐ 12 Explain how antibiotics work to limit bacterial growth. Distinguish between bactericidal and bacteriostatic actions and explain the significance of these. **173**
- ☐ 13 **PRAC** Investigate the effect of an antimicrobial on the growth of a microorganism by measuring zones of inhibition. **150**

165 Infection and Disease

Key Idea: The term disease encompasses any disorder in the structure or function of an animal or plant. It may be caused by an infectious agent or a spontaneous change in the body. Disease can be divided into two main types: infectious disease and non-infectious disease. Infectious disease is caused by infectious agents called pathogens, which include bacteria and viruses. Non-infectious disease is caused by damage or changes to the body which may occur because of genetic defects which may be congenital (e.g. type 1 diabetes) or caused by environment effects (e.g. skin cancer).

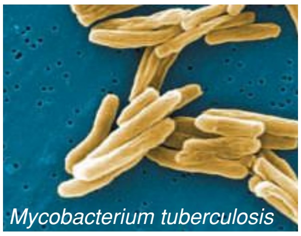
Infectious disease

The pathogens causing infectious diseases may be cellular (e.g. bacteria and protists) or non cellular (e.g. viruses and prions). Pathogens produce molecules (called **virulence factors**) that make them more effective at infecting their host. These virulence factors are commonly antigenic (capable of causing an immune reaction in the host).

Cellular pathogens

Bacterial pathogens

Pathogenic bacteria can be transmitted through food, water, air, or by direct contact. Although bacteria have historically caused widespread and devastating diseases, the discovery and use of antibiotics and aseptic techniques have significantly reduced these.


Mycobacterium tuberculosis

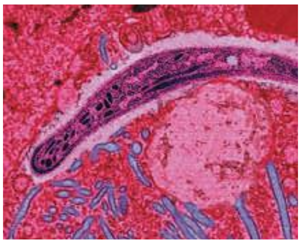
CDC: Janice Haney Carr

Fungal pathogens

Pathogenic fungi are more common in plants than in animals. They spread by spores and the infections they cause are generally chronic (long-lasting) infections because fungi grow relatively slowly.

Protistan pathogens

Protistans are a large and diverse group of eukaryotes. A number of species are significant pathogens of animals or plants. Pathogenic protists have very complex life cycles, often involving a number of different hosts and several different life stages.



Non-cellular pathogens

Viral pathogens

A virus is a highly infectious pathogen that infects living cells (including bacterial cells) and uses the cell's metabolic machinery to replicate. Viruses consist of a protein envelope surrounding the nuclear material that can be either DNA or RNA.

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Prions

Prions are misfolded infectious proteins that have pathogenic properties. They contain no genetic material so do not replicate in the usual way. Instead, an infectious prion binds to a normal protein and causes it to change shape and become infectious. Prions cause degenerative nervous diseases in mammals including scrapie in sheep, BSE in cattle, and kuru in humans.

Non-infectious disease

Non infectious diseases are not transmitted from person to person and are often caused by genetic or lifestyle factors.

Environmental diseases

These are caused by external factors such as a lack of sunlight or vitamins. These diseases also include diseases caused by lifestyle choices, such as drinking too much alcohol or smoking. Environmental diseases include cancer, diseases of affluence and various social diseases (below):

Emmanuelm cc3.0

Cancer

Cancer is caused by mutations in the genes that keep cell growth and division in check. Cancer causes the cells to grow and divide continuously, causing tumors and affecting organ function.

Diseases of affluence

This is a relatively new term that encompasses a wide range of environmental diseases that are more commonly seen in relatively wealthy (and often Western) societies. They include obesity, mental health issues, and cardiovascular diseases. They are often said to contrast so-called "poverty diseases", such as severe malnutrition.

Inherited diseases

These are genetic diseases caused by mutations (DNA errors) carried by the parents and passed to the offspring. They may also occur spontaneously during the development of the sperm or egg. Inherited diseases include Huntington's disease and cystic fibrosis (right).

Autoimmune diseases

Occasionally the immune system of the body begins to attack parts of its own body. These diseases include type 1 diabetes and multiple sclerosis. Type 1 diabetics must inject insulin because their insulin-producing cells have been destroyed (right).

SHE 1 43

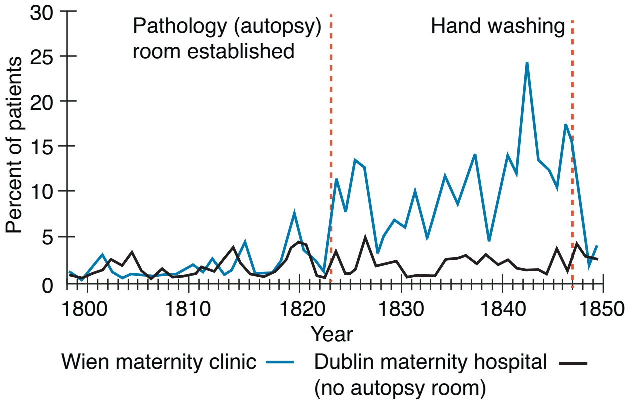
ISBN: 978-1-927309-83-4

Germ theory and disease transmission

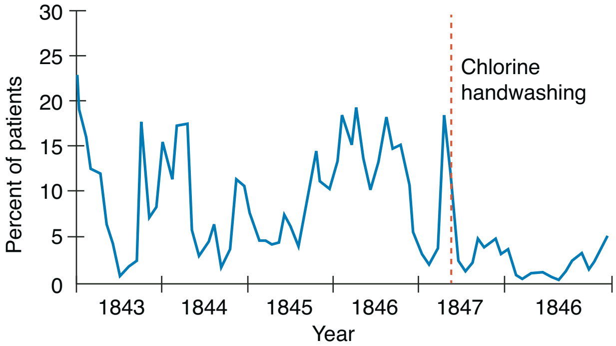
Germ theory, the idea that infections are caused by infectious microscopic agents, was developed around the middle of the nineteenth century. Since the development of the modern scientific method based on controlled experiment and observation, we are now able to identify and treat a vast range of diseases.

Ingaz Semmelwies was an assistant professor at the Vienna General Hospital in which there were two maternity clinics. The first clinic taught medical students and the second taught midwives. Semmelwies noticed that the first clinic always had higher mortality rates in the mothers from fever after childbirth (postpartum) than the second clinic. He realised that the medical students were carrying some sort of infectious agent from the bodies they were dissecting in the autopsy room to the maternity ward, but that the midwives were not. He instigated a policy of hand washing with a solution of chlorinated lime. The result was an almost immediate substantial drop in mortality.

Mortality by postpartum fever in Wien maternity clinic and Dublin maternity hospital

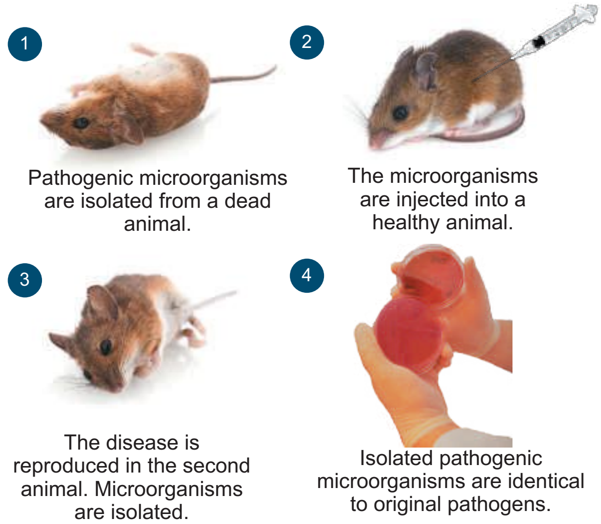


Mortality by postpartum fever



Robert Koch showed that a specific disease was caused by a specific pathogenic (disease-causing) agent. He developed what are now known as Koch's postulates.

Koch's postulates



Koch isolated bacteria from a diseased animal, then injected them into a healthy animal, causing it to exhibit identical symptoms to the first. This demonstrated that a specific infectious disease (e.g. anthrax) was caused by a specific microorganism (Bacillus anthracis). Koch used the procedure to identify the bacteria that caused anthrax and tuberculosis.

Koch's findings are summarised as Koch's postulates:

1. The same pathogen must be present in every case of the disease.
2. The pathogen must be isolated from the diseased host and grown in pure culture.
3. The pathogen from the pure culture must then cause the disease when it is inoculated into a healthy, susceptible animal.
4. The pathogen must be isolated from the inoculated animal and shown to be the original organism.

1. (a) What is the difference between infectious and non-infectious disease? ______________________

____

(b) What are the two main types of pathogens and give examples? ______________________

____

2. What was the significance of Koch's contribution to germ theory? ______________________

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3. Describe the evidence supporting Semmelwies's theory that an infectious agent was responsible for postpartum fever:

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166 Bacterial Diseases

Key Idea: Pathogenic bacteria are responsible for some of the world's most devastating diseases of plants and animals.

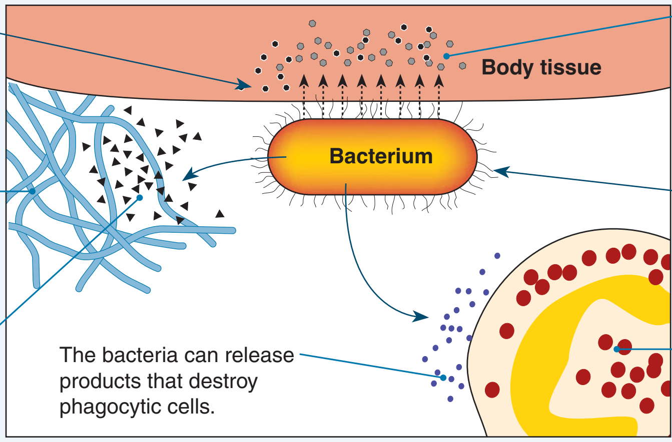
Relatively few of the world's bacterial species cause disease. Those that do (the pathogenic bacteria), have a range of adaptations that enable them to penetrate the defences of a host and cause infection (below). Bacterial diseases are commonly transmitted through food, water, air, or by direct contact. The natural source of infection of a disease varies from species to species, ranging from humans and other organisms, to sewage or contaminated water. Much of our control of bacterial disease is achieved through identifying reservoirs of infection and limiting the routes of transmission.

How bacteria invade a host's tissue

Toxins: Bacterial toxins can act locally to promote bacterial invasion (e.g. the enzymes that degrade collagen), or they may have cytotoxic activity and destroy cells directly.

Fibrin: Fibrous threads of protein are deposited when blood clots. This action by the host effectively limits the movement of pathogens in infected areas.

Enzymes are released that break down fibrin, allowing the bacteria greater freedom of movement.

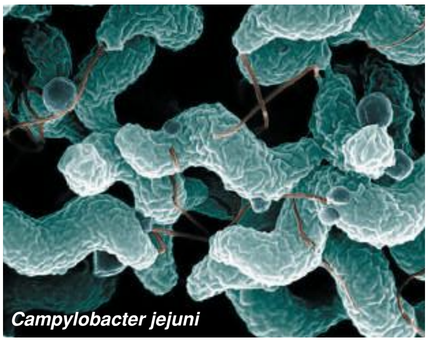


The bacterium releases enzymes that degrade the connective tissue of the host, allowing the spread of infection.

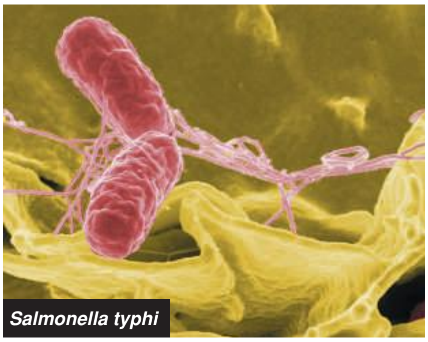
Fimbriae are fine, threadlike extensions from the bacterial cell. The bacteria use them to attach to the mucous membranes and directly attack the host tissues.

Phagocyte: These white blood cells are very effective in identifying and destroying foreign cells such as pathogens.

Methods of bacterial transmission


Campylobacter jejuni

NIH


Salmonella typhi

CDC

CDC

Foodborne bacterial diseases

Bacterial foodborne illnesses are caused by consuming food or beverages contaminated with bacteria or their toxins. Examples include *Salmonella* food poisoning and *Campylobacter* infection. Symptoms of bacterial food poisoning include fever, abdominal cramps, and diarrhoea. Some are associated with consuming raw or undercooked poultry.

Waterborne bacterial diseases

Waterborne bacterial pathogens are responsible for a number of serious diarrhoeal illnesses, including typhoid and cholera. Transmission of these diseases is usually through faecal contamination of drinking water. The fever and diarrhoea associated with such diseases is responsible for hundreds of thousands of deaths annually in countries with poor sanitation.

Airborne bacterial diseases

Airborne pathogens are transmitted on dust particles or droplets when people cough, sneeze, or exhale. Vaccination against certain airborne bacteria has been highly successful. Whooping cough (above) is a potentially fatal respiratory disease caused by the bacterial pertussis toxin. The prevalence of this disease has declined dramatically following the introduction of immunisation programmes.

1. Describe the specific adaptations of bacteria that contribute to their ability to cause disease:

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2. What are the most common ways in which bacteria area spread? _______________________

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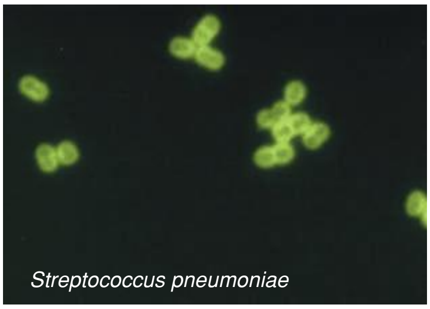
Examples of bacterial disease

Tetanus
Tetanus is a condition characterised by prolonged, strong contractions of the skeletal muscles. It is caused by the toxin tetanospasmin, produced by the bacteria *Clostridium tetani* an anaerobic bacterium commonly found in the soil. Infection is usually through a puncture wound that becomes contaminated with soil or dirt.

CDC

Bacterial meningitis
Bacterial meningitis is most commonly caused by the bacterial pathogens *Neisseria meningitidis* and *Streptococcus pneumoniae* (below). The bacteria infect the membranes around the brain (the meninges) causing headaches, fever, rashes and sometimes death. The fatality rate is between 10%-20%.



Streptococcus pneumoniae

Plant Crown Gall
Crown gall is a tumour-like growth in plants caused by the soil bacterium *Agrobacterium tumefaciens*. The gall is produced when the bacterium transfers a circular piece of DNA (the tumour-inducing or *Ti* plasmid) to the plant cell. *A. tumefaciens* is now commonly used in biotechnology to insert new genes into plants for genetic modification.

USDA

3. Why is immunisation often the best option for controlling airborne bacterial diseases?

4. Why is it not good practice to chop vegetables on the same chopping board as is used to prepare raw chicken?

5. Why are there often outbreaks (or risks of outbreak) of bacterial diseases such as typhoid and cholera after large scale natural disasters, such as large scale earthquakes or tsunamis?

6. How can simple measures, such as washing hands before eating, reduce the incidence of bacterial diseases?

7. Explain why *Agrobacterium tumefaciens* is of particular interest to scientists:

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167 Fungal Diseases

Key Idea: Pathogenic fungi are rare in animals, but they can cause infections that are long lasting and difficult to treat.

All fungi are heterotrophic, requiring organic compounds for energy and carbon. They may be parasitic or saprotrophic, obtaining nutrition by the extracellular digestion of living or dead organic matter. Very few fungi are pathogenic to animals, although thousands of fungal species are plant pathogens. They spread by spores and the infections they cause are generally **chronic** (long-lasting) infections because fungi grow relatively slowly. Fungal diseases are categorised into three broad groups (below), the most common being superficial infections of the skin. Of great concern recently is the spread of a fungal pathogen in amphibian populations. Amphibian chytrid fungus disease has been linked to the dramatic decline in amphibian populations globally. Amphibians rely on their skin for osmoregulation and oxygen uptake, so they are particularly vulnerable to pathogens that compromise its integrity.

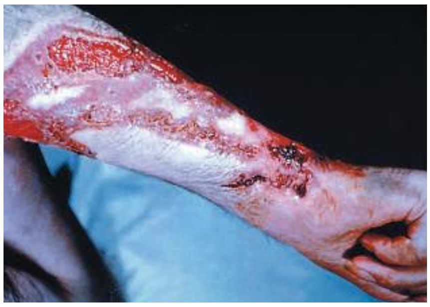
Types of fungal infection

CDC

Systemic Infections are usually ones that occur deep inside the body, affecting internal organs, such as the lungs, bones, heart, and urinary tract. They often start in the lungs by inhalation of the spores and spread throughout the body. e.g. candidiasis in the kidney above.

CDC

Cutaneous (superficial) infection: Infection that affects the skin, hair, nails, genital organs, and inside of mouth. Contracted through contact with spores, e.g. trichosporosis infection of the toenails above. They are slow growing and difficult to treat.



Subcutaneous Infection: Rare infection of the fatty connective tissue beneath the skin. Contracted through direct implantation of the spores into the skin via a scratch or puncture wound, e.g. sporotrichosis (above) caused by the fungus *Sporothrix schenckii.*

Chytridiomycosis

Chytridiomycosis is a waterborne disease of amphibians caused by the fungi *Batrachochytrium dendrobatidis*. It disperses via motile spores called zoospores, which enter the host via the skin, although much of how new hosts are infected is still unknown. It can be fatal to infected frogs within 10-18 days.

Batrachochytrium dendrobatidis is found to various parts of Australia, notably on the east coast, Adelaide, south-west Western Australia and the Kimberley region of WA.

Chytridiomycosis has been implicated in the dramatic population declines of frog species including the *Litoria nannotis* (waterfall frog), *Litoria rheocola* (common mistfrog). It is also implicated in the extinction of at least four species of Australian frog.

Forrest Brem CC 2.5 Riders of a Modern-Day Ark. Gewin V. PLoS Biology 6(1), e24 doi:10.1371/journal.pbio.0060024.

Frog killed by chytridiomycosis. Note the reddening of the skin which is characteristic of the disease.

1. Describe two features of fungal diseases:

2. Why is it often difficult to treat a fungal infection?

3. (a) Suggest one way in which chytridiomycosis causes death in infected frogs:

   (b) Suggest why amphibians are so vulnerable to chytridiomycosis:

   (c) Frogs are popular aquarium pets in many countries. How might this be contributing to the spread of the disease?

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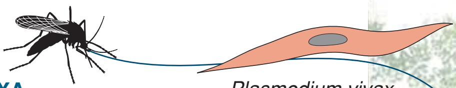
168 Protistan Diseases

Key Idea: Protistans are a large and extremely diverse group of eukaryotic organisms. A number of species are significant pathogens of animals or plants.

The protists are a group of unicellular or colonial eukaryotes. Most inhabit water or soil habitats and relatively few cause disease. However, a number of species are highly specialised pathogens. These include species of the parasitic genus *Plasmodium*, which cause malaria in humans, and species of the oomycete genus *Phytophthora*, which cause devastating dieback and blight in a number of plant species. Pathogenic protists have very complex life cycles, often involving a number of different hosts and several different life stages. Both oomycetes and plasmodia, for example, have infective motile stages as well as resistant resting stages.

AMOEBAE

Amoebae move by extending projections of their cytoplasm. Several pathogenic amoebae infect humans and feed mainly on red blood cells. People become infected with the pathogen for amoebic microencephalitis while swimming in warm bodies of fresh water or hot springs, when the waterborne cysts pass across mucous membranes and infect blood, brain, and spinal cord. It's almost always fatal.



Plasmodium vivax

APICOMPLEXA

These protozoans are not mobile and tend to be intracellular parasites. They use special enzymes to penetrate the host's tissues. They have complex life cycles involving transmission between several host species. Apicomplexans include *Plasmodium*, which is spread by mosquito vectors and causes malaria.

Plasmodium sporozoite stage moving through the cytoplasm of the intestinal epithelia

Ute Frevert, Plos

Giardia trophozoite, SEM

CDC

FLAGELLATES

Flagellates are usually spindle-shaped, with flagella projecting from the front end. The whiplike motion of the flagella pulls the cells through their environment. *Giardia* (left) is found in the small intestine of mammals. It is passed in the faeces and its life cycle alternates between an actively swimming trophozoite (left) and an infective, resistant cyst.

Phytophthora dieback

Phytophthora dieback is caused by the soil-borne water mould *Phytophthora cinnamomi*. Although it was originally classified as a fungus, *Phytophthora* is now included in the Protista. Flagellated zoospores enter the plant near the growing tip of the roots where they germinate, produce fungal-like hyphae, and absorb carbohydrates in the root. This eventually destroys the internal structure of the roots and causes the death of the plant.

Phytophthora cinnamomi is one of the world's most invasive plant pathogens. In Australia, it is responsible for the dieback of *Eucalyptus* trees especially in the Jarrah Forest bioregion of Western Australia. *Phytophthora* dieback can be treated with various fungicides including the use of phosphite salts (e.g. calcium phosphite).

Edward L. Barnard, Florida Department of Agriculture and Consumer Services, Bugwood.org

Phytophthora infection in a pine tree. Note the stunted growth. High water tables and excess irrigation provide suitable conditions root infections.

John H. Ghent, USDA Forest Service, Bugwood.org

Phytophthora infection in a pine tree showing rotted area near roots. Once a host is infected, water flow through the xylem is reduced via wilt-inducing toxins.

1. Several parasitic protozoans causing diseases in humans use other animal species as hosts for part of their life cycle. Identify the host (including class and genus) that is involved in part of the life cycle for malaria:

___

2. Why does infection by *Phytophthora cinnamomi* cause stunted growth and death in plants? ___

___

___

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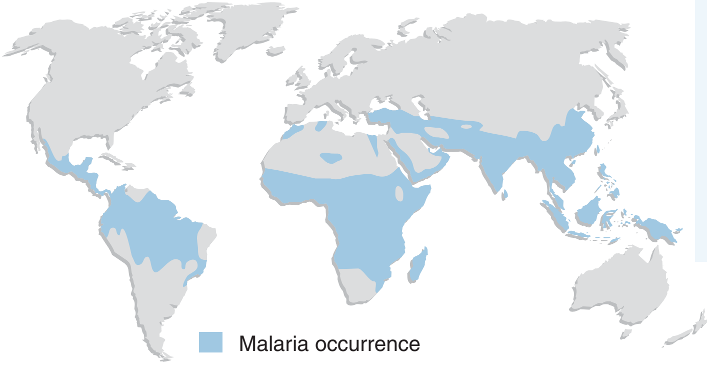
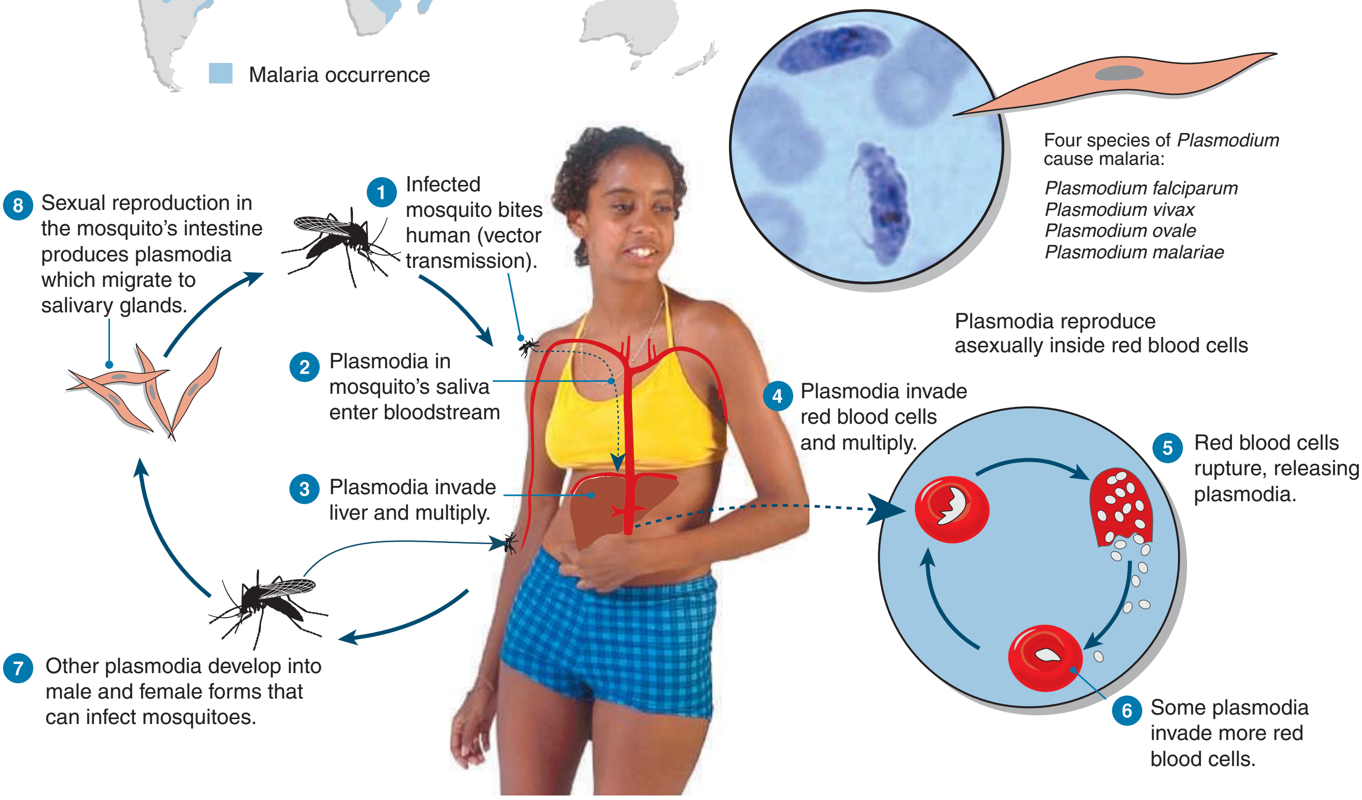
Malaria is caused by a protistan parasite

- Malaria is a disease caused by protistan parasites of the genus *Plasmodium*. The plasmodia have a life cycle involving two hosts, *Anopheles* mosquitoes, which act as a **vector** for transmission of the parasite, and humans. Humans become infected when bitten by mosquitoes infected with the protozoans. In their human host, the plasmodia infect red blood cells (RBCs) and multiply inside the cells by asexual reproduction.
- Four *Plasmodium* species cause malaria, ranging in severity from relatively mild to fatal. *Falciparum* malaria is the most severe because it affects red blood cells of all ages. Destruction of the RBCs results in a condition called haemolytic anaemia (loss of RBCs through lysis). Infected blood cells also become sticky and block blood vessels to vital organs such as the kidneys and brain.



Malaria is a major health problem in tropical regions where the climate is warm and wet enough to support breeding populations of the mosquito vector. Malaria affects more than 300 million people a year in equatorial regions (left). Cases in Australia only result when infected travellers return from these regions, although Northern Australia could harbour malarial mosquitoes if the global climate warms significantly.



3. How does a *Plasmodium* parasite enter the body? ____________________

____

4. What aspects of the biology of this pathogen could make it difficult to control? ____________________

____

____

5. (a) What biological factors are important in the global occurrence of malaria? ____________________

____

(b) What measures could be cost effective in controlling the number of new malaria infections? ____________________

____

____

6. Why is global warming expected to increase the geographical range of malaria? ____________________

____

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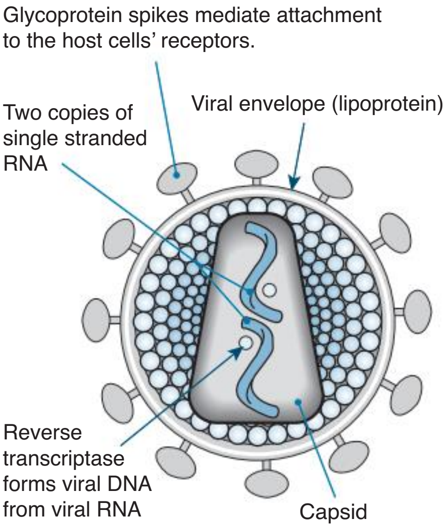
169 Viral Diseases

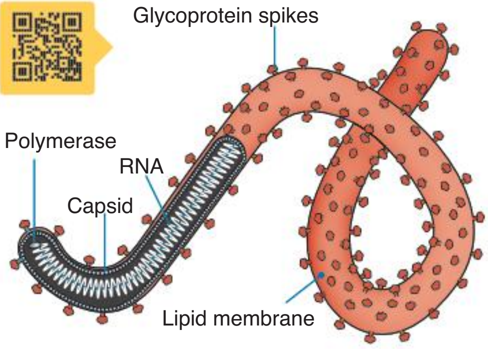
Key Idea: A virus is an infectious, highly specialised intracellular parasite. They are acellular and non-living.

Viruses are disease-causing agents (**pathogens**), which replicate (reproduce themselves) only inside the living cells of other organisms. Viruses are acellular, meaning they are not made up of cells, so they do not conform to the existing criteria upon which a five or six kingdom classification system is based. A typical virus contains genetic material (DNA or RNA) encased in a protein coat (capsid). Some viruses have an additional membrane, called an envelope, surrounding the capsid. Many viruses have glycoprotein receptor spikes on their envelopes that help them to attach to surface of the host cell they are infecting. Viruses vary greatly in their appearance and the type of host they infect (below).

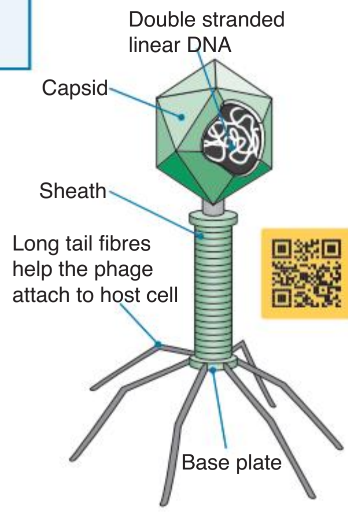
Viruses are not organisms! Viruses are metabolically inert until they are inside the host cell and hijacking its metabolic machinery to make new viral particles. However, they are often called microorganisms.



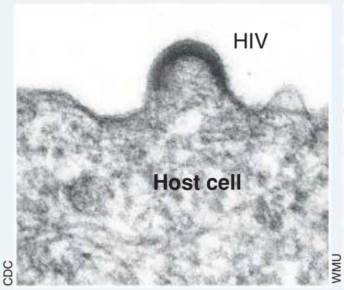
Structure of HIV, an enveloped retrovirus.

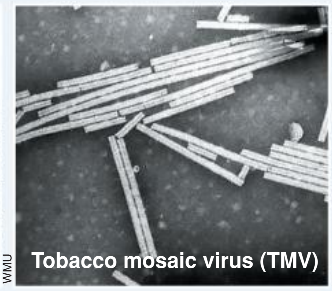


Structure of Ebola virus, an RNA filovirus that causes Ebola haemorrhagic fever.



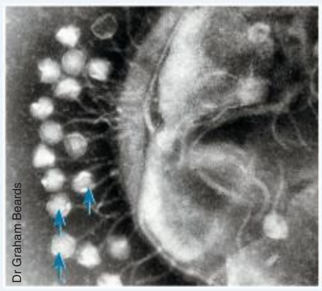
Structure of Lambda phage, a bacteriophage that infects E.coli.





After replication, new viral particles (**virons**) leave the host cell to infect more cells. In animals, enveloped viruses bud from the host cell, e.g. HIV (above left). Plant viruses cannot bud from the host cell due to the rigid cell wall. Instead, plant viruses, e.g. TMV (above right), move through the plasmodesmata connecting plant cells.

Viruses cause a wide variety of common human diseases, e.g. colds, influenza, and life-threatening diseases such as AIDS and Ebola (above).



Bacteriophages (arrowed) infect bacteria. They use tail fibres to attach to the host cell and a contractile region below the capsid to inject their DNA into the cell.

1. What is the significance of viruses being non-living? ____________________

____

____

2. Describe the basic structure of a generalised virus, identifying the features they all have in common: ____________________

____

____

3. Describe the purpose of the following:

(a) Glycoprotein spikes: ____________________

(b) A bacteriophage's tail fibres: ____________________

(c) Protein capsid: ____________________

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170 HIV

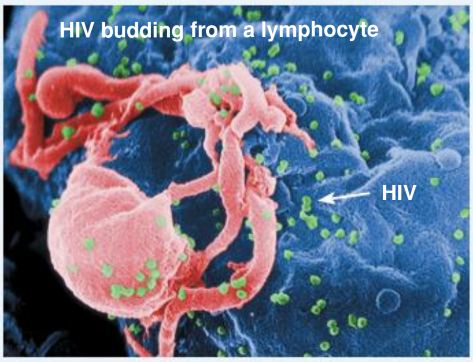
Key Idea: The human immunodeficiency virus (HIV) infects lymphocyte cells, eventually causing AIDS, a fatal disease, which acts by impairing immune system function.

Immune deficiency occurs when the body's immune system has limited (or no) ability to fight infectious disease. People with immune deficiency diseases become sick more often and for longer periods than a healthy individual. Some types of immune deficiency are inherited, but others develop as a result of another factor (e.g. chemotherapy, malnutrition, or infectious disease). HIV (human immunodeficiency virus) causes immune deficiency by destroying T helper cells, which are central to cellular immunity. Over time, a disease called **AIDS** (acquired immunodeficiency syndrome) develops and the immune system progressively loses its ability to fight infection. There is no cure or vaccine for HIV, but drugs that can slow the progress of the disease are now quite effective.

HIV infects T helper cells

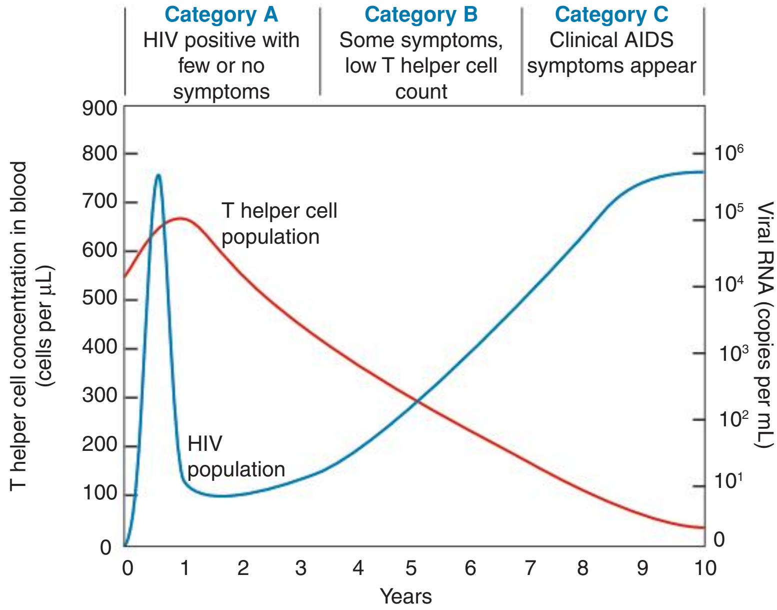
HIV infects T helper cells. It uses the cells to replicate itself in great numbers, then the newly formed viral particles exit the cell to infect more T helper cells. Many T helper cells are destroyed by the viral replication. Because of their role in cellular immunity, T helper cell destruction recruits more T cells, accelerating the infection of new cells.

Once the T helper cell population becomes depleted, the immune system's ability to fight infection is severely compromised.



CDC

The graph below shows the relationship between the level of HIV infection and the number of T helper cells. AIDS is only the end stage of an HIV infection. Shortly after the initial infection, HIV antibodies appear in the blood. There are three clinical categories during progression of the disease.



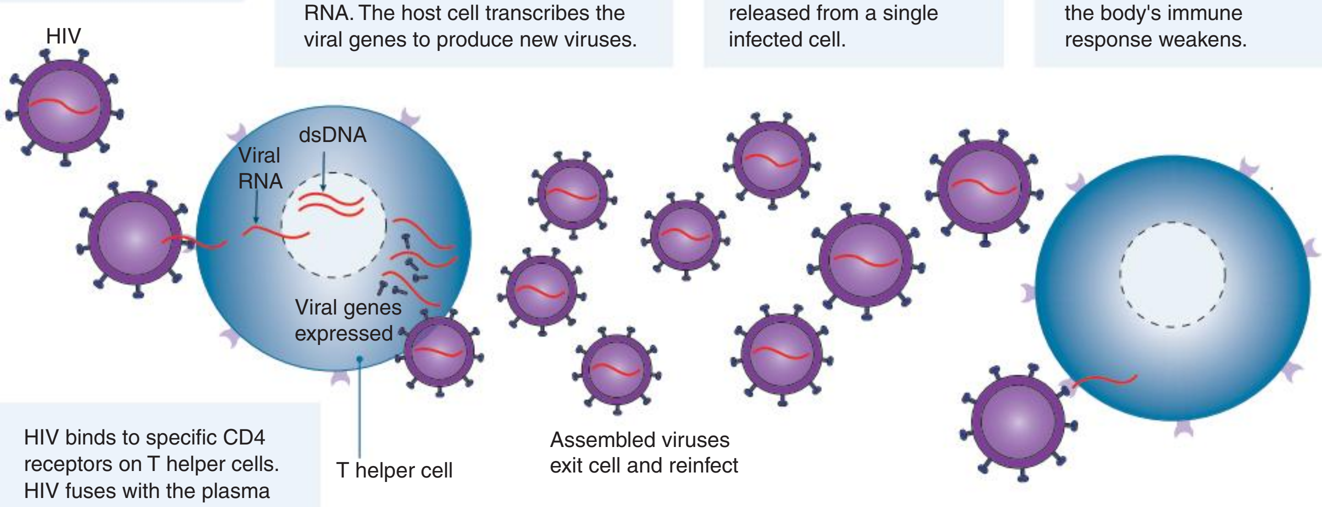
HIV uses the cellular machinery of T helper cells to replicate

The genetic material of HIV is a single strand of RNA.

HIV hijacks the T helper cells' machinery to replicate itself. Reverse transcriptase produces double stranded DNA (dsDNA) from the viral RNA. The host cell transcribes the viral genes to produce new viruses.

The new HIV particles bud from the T helper cell. Between 1000 and 3000 new HIV particles can be released from a single infected cell.

The HIV particles mature and infect more T helper cells. As more T helper cells become infected, the body's immune response weakens.



HIV binds to specific CD4 receptors on T helper cells. HIV fuses with the plasma membrane of the T helper cell. Its RNA enters the cell.

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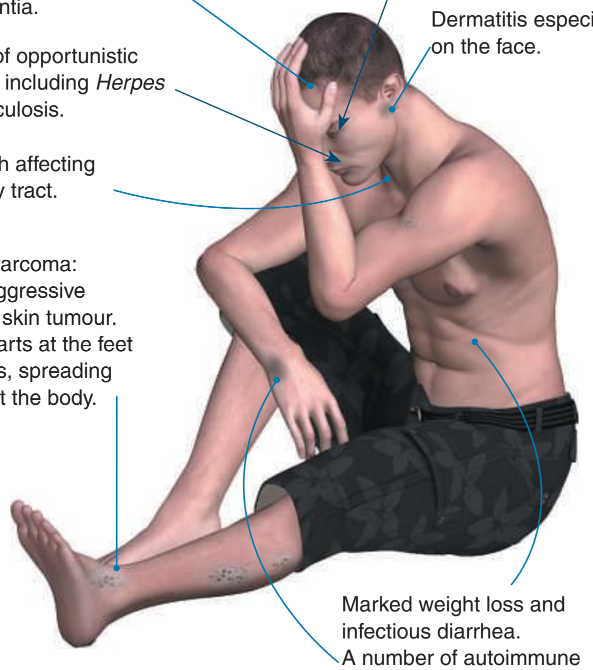
AIDS: The end stage of an HIV infection

HIV/AIDS is a spectrum of disorders (right) arising as a consequence of impaired immune function, which prevents the body detecting and destroying pathogens or damaged cells.

People with healthy immune systems can fight off the challenges of pathogens and are able to detect and destroy damaged (pre-cancerous) cells. However, people with HIV are susceptible to all pathogens because their resistance to disease is so low. What's more, loss of the T cell population compromises the ability of HIV-infected people to detect and destroy pre-cancerous cells. Rare cancers are a common symptom of HIV/AIDS.

Antibiotics can be used to treat some of the infections contracted due to the reduced immune system (e.g. tuberculosis), but they cannot be used to treat the HIV infection itself. Antibiotics work by targeting prokaryotic (bacterial) metabolism and so are ineffective against a non-cellular pathogen that hijacks eukaryotic metabolism in order to replicate. Although there is currently no cure of HIV/AIDS, some drugs can slow the progress of the disease by interfering with the replication of HIV and slowing the advance of the disease.



1. (a) What type of cells does HIV infect? ______________________

   (b) How does HIV recognise this type of cell? ______________________

   ____

   (c) What is the role of reverse transcriptase in HIV replication? ______________________

   ____

   ____

2. Study the graph on the previous page showing how HIV affects the number of T helper cells. Describe how the viral population changes with the progression of the disease:

   ____

   ____

   ____

3. (a) What effect does HIV have the cells of the immune system? ______________________

   ____

   (b) Describe the effect of this change on the long-term health of a person with HIV: ______________________

   ____

   ____

4. (a) Why is the purpose of antibiotics in treatment of HIV/AIDS? ______________________

   ____

   ____

   (b) Why are antibiotics ineffective against the HIV infection itself? ______________________

   ____

   ____

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171 Prions

Key Idea: Prions are misfolded infectious proteins that can propagate by causing misfolding in the original protein type.

Until recently, all pathogens were thought to contain some form of nucleic acid. We now know that particular proteins, called **prions**, are capable of causing infection. Prions have been spread by eating contaminated meat and, because they resist normal sterilisation methods, they can be spread on surgical instruments. Prions are produced by mutations in the gene coding for a normal cell protein (PrP). They cause a group of degenerative nervous diseases in mammals called transmissible spongiform encephalopathies (TSE). They include scrapie in sheep, **BSE** in cattle, and **kuru** in humans. Different mutations of the PrP gene are responsible in each case.

The disease **kuru** first brought prion diseases to prominence in the 1950s. It occurred in the geographically isolated tribes in the Fore highlands of Papua New Guinea. These people were eating the brain tissue of dead relatives for religious reasons.

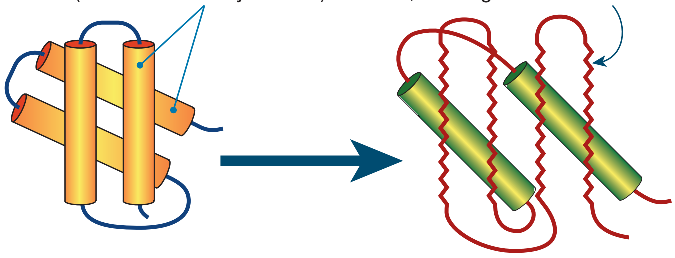
Normal and infectious prions have the same primary structure, so go unchallenged by the immune system. If the infectious prion is from another species (as in vCJD) there is an initial immune response but this is shut down as the infectious protein converts more and more of the body's own PrP^{C} to PrP^{SC}.

Prion diseases of humans (and cause)
All these diseases are characterised by dementia and loss of coordination. There may be other symptoms as well.

- Kuru (infection through cannibalism)
- Variant Creutzfeldt-Jacob Disease (vCJD) (infection)
- Classical Creutzfeldt-Jacob Disease (infection or mutation)
- Fatal Familial Insomnia (inherited mutation)

Infectious prion proteins

A shape change transforms the harmless protein into an infectious **prion**. The change may be caused by a point mutation in the encoding gene. The normal (common) form of the protein is denoted PrP^{C}, whereas the abnormal form is denoted PrP^{SC} (after scrapie, the prototype prion).

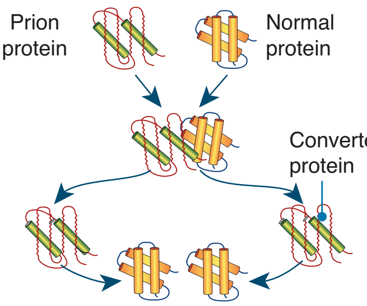


Propagation of the prion protein

Infectious protein (prion) has an unusual shape and binds to the normal form of the protein.

The normal protein is converted to the infectious prion.

The original and newly formed prions attack other nearby proteins. In time, prions accumulate to dangerous levels.



1. What is the main feature of prions distinguishing them from other infectious agents? ______

2. How does a prion's mode of transmission make it a successful agent of disease? ______

3. What is the source of infection for people with variant CJD? ______

4. How did the cultural practices of highland tribes in PNG enable the spread of kuru? ______

5. An epidemic of BSE in the UK in the 1990s had its origin in the practice of processing waste parts of cattle (particularly nervous tissue) and recycling them into cattle feed. Infected cattle subsequently entered the human food chain and were linked to cases of vCJD. Explain why it is poor practice to process an animal and feed it back to the same species: ______

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172 Transmission of Disease

Key Idea: Infectious disease can spread rapidly within and between regions given the right conditions.

The human body, like that of other large animals, is constantly exposed to a wide range of potential parasites and pathogens. Transmission and spread of a pathogen depends on its rate of growth, the density of the host population, the mobility of the host population, and the mode of transmission. The transmission of infectious diseases can be virtually eliminated by observing hygienic practices, e.g. chlorinating drinking water and by providing adequate sanitation.

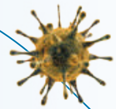
Transmission and spread

Most pathogens, once inside the body, multiply rapidly, producing symptoms and making the host infectious within a few days. Others take longer to present symptoms. The infectious period can last from a few days to weeks, but in some cases the host may be infectious for long periods of time.

Human cities can contain millions of people, often living very closely together. In these congested conditions, infectious diseases can spread rapidly, especially if sanitation or personal hygiene is poor, or if seasonal weather produces conditions favourable to spread of the pathogen. High speed transport can help spread a pathogen around a region very quickly.

The mode of transmission affects how quickly a pathogen spreads. Direct person to person contact (i.e. touching) is a slower method of spreading, while spreading via mucus droplets coughed into the air or by animal **vectors** (such as mosquitoes) can help a pathogen spread quickly.

Portals of entry



Influenzavirus

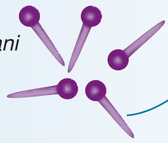
Respiratory tract

The mouth and nose are major entry points for pathogens, particularly airborne viruses, which are inhaled from the expelled mucus of infected people.
Examples: tuberculosis (TB), whooping cough, meningococcal meningitis, influenza, measles, rubella, chickenpox.

Salmonella typhi causes typhoid fever

Gastrointestinal tract

Food and water are often contaminated with microorganisms, but most of these are destroyed in the stomach.
Examples: cholera, typhoid fever, mumps, hepatitis A, poliomyelitis, salmonellosis.



Clostridium tetani causes tetanus

Breaking the skin surface

The skin provides an effective barrier to most pathogens, but cuts and abrasions allow pathogens to penetrate.
Examples: tetanus, gas gangrene, hepatitis B, rabies, malaria, and HIV.

HIV

Urinogenital openings

Urinogenital openings provide entry points for the pathogens responsible for sexually transmitted infections (STIs) and other opportunistic infections (i.e. thrush).
Examples: gonorrhoea, HIV.

1. Why can disease spread quickly in congested human cities? ______________________________

____

____

2. Why would transmission by direct touch be slower than transmission by coughing or sneezing? ______________________________

____

____

____

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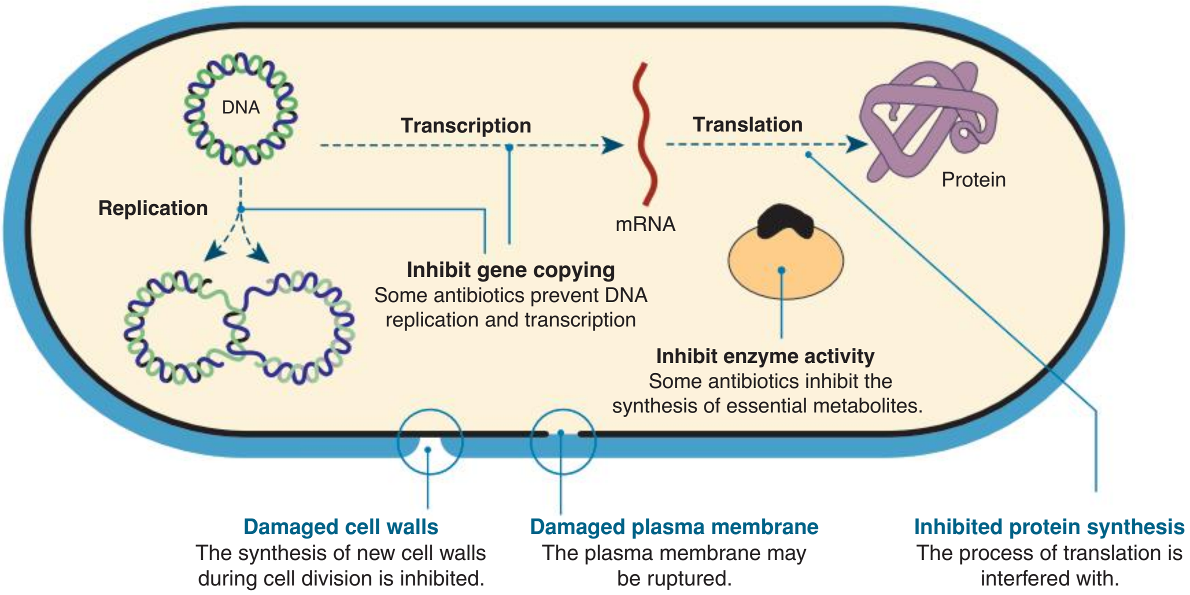
173 Testing Antibiotics

Key Idea: Antibiotics are antimicrobial chemicals that kill bacteria (bactericidal) or inhibit their growth (bacteriostatic).

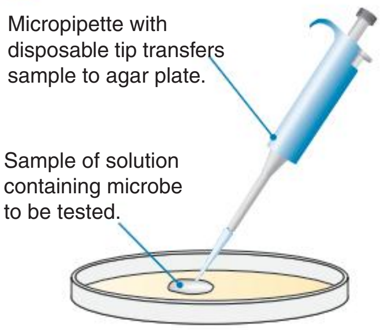
Antibiotics are chemicals that act against bacterial infections by either killing the bacteria (**bactericidal** action) or preventing them from growing (**bacteriostatic** action). Antibiotics interfere with bacterial growth by disrupting key aspects of bacterial metabolism (below). Antibiotics are ineffective against viruses because viruses lack the structure and metabolic machinery that antibiotics target. Antibiotics are produced naturally by bacteria and fungi to kill or inhibit competitors or pathogens, but most modern antibiotics are semi-synthetic modifications of these natural compounds.

How antibiotics work

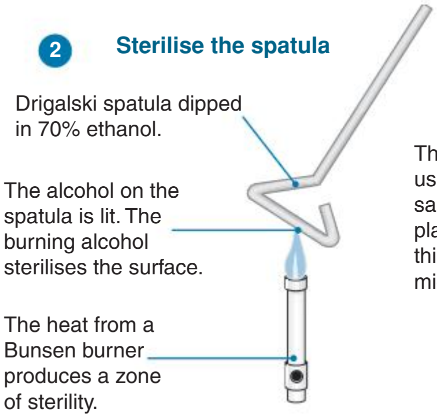


Testing effectiveness of antibiotics

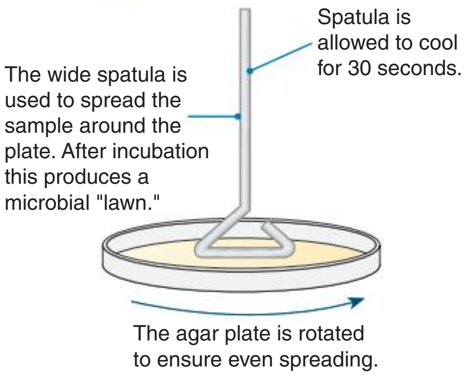
1 Pipette a sample



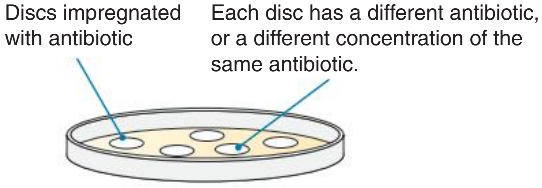
2 Sterilise the spatula



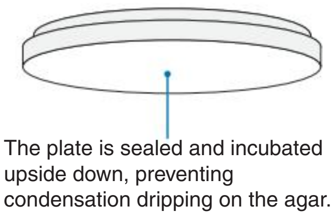
3 Spread the sample



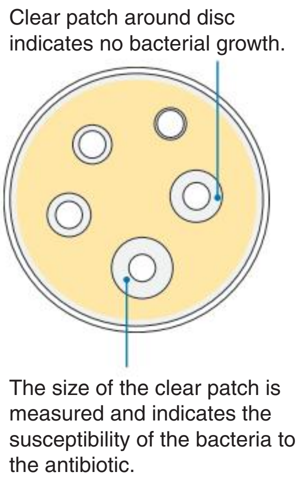
4 Antibiotic discs



5 Incubate plate



6 Analyse results



Clear area around antibiotic discs

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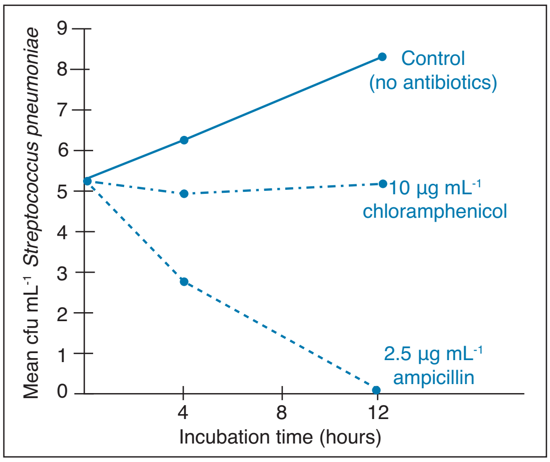
1. Why are viruses not affected by antibiotics? ______________________________

2. Distinguish between bacteriostatic and bactericidal: ______________________________

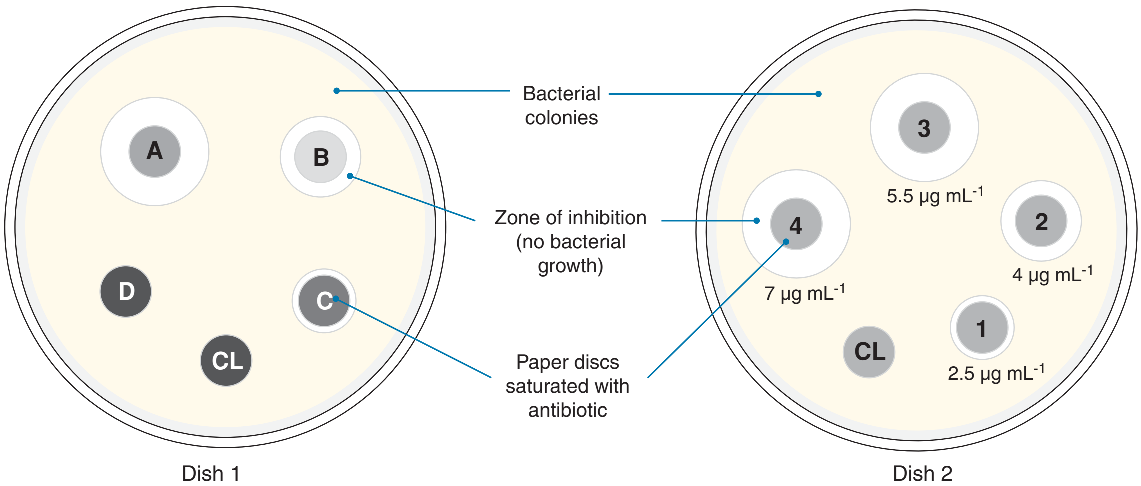
3. The graph (right) shows the effects of two antibiotics. Identify the antibiotic with a bacteriostatic action and the antibiotic with a bactericidal action. Explain your choice:

Bacteriostatic: ______________________________

Bactericidal: ______________________________



4. Two students carried out an experiment to determine the effect of antibiotics on bacteria. They placed discs saturated with antibiotic on petri dishes evenly coated with bacterial colonies. Dish 1 contained four different antibiotics labelled A to D and a control labelled CL. Dish 2 contained four different concentrations of a single antibiotic and a control labelled CL.



(a) Which was the most effective antibiotic on Dish 1? ______________________________

(b) Which was the most effective concentration on Dish 2? ______________________________

(c) Explain your choice in question 5(b): ______________________________

5. Referring to the procedure for testing antibiotics on the opposite page:

(a) Why is the agar plate incubated upside down? ______________________________

(b) Why is the spatula dipped in alcohol and heated? ______________________________

(c) How would you measure the clear zone around the antibiotic discs? ______________________________

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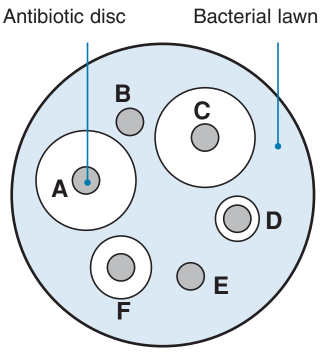
174 KEY TERMS AND IDEAS: Did You Get It?

1. Test your vocabulary by matching each term to its definition, as identified by its preceding letter code.

antibiotic	A	Any disease caused by the invasion of a host by a pathogen which grows and multiplies in the body and is transmissible to others.
bacteria	B	A type of disease that cannot be transmitted between individuals.
disease	C	A substance that can kill bacteria or inhibit their growth.
infectious disease	D	A disease-causing organism.
non-infectious disease	E	Single celled microorganisms surrounded by a cell wall containing the substance peptidoglycan. Some are pathogens responsible for serious diseases in humans.
pathogen	F	A non-cellular obligate intracellular parasite, requiring a living host to reproduce. Does not respond to antibiotics.
virus	G	An abnormal condition of the body when bodily functions are impaired.

2. An agar plate with a bacterial lawn was used to test the effectiveness of different antibiotics at inhibiting growth. Six paper discs impregnated with six different antibiotics were placed on the law. The result after 48 hours incubation is shown:



(a) Which antibiotic(s) were the most effective? ______________________

(b) Which antibiotics were the least effective? ______________________

(c) Antibiotics, A, C, D, and F are from the penicillin family of antibiotics. What does this tell you about the bacteria involved in this test?

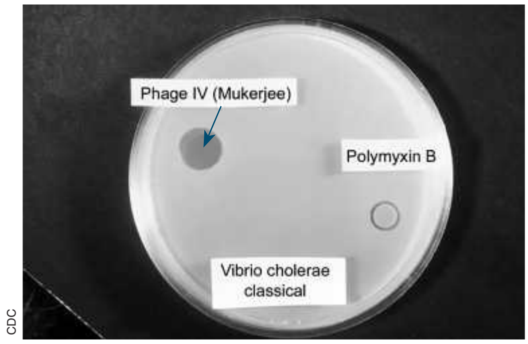
____

____

3. The table below lists some infectious diseases. Complete the table by naming the type of pathogen that causes the disease (bacteria, virus, protist), and the symptoms of the disease. You may need to do some extra research.

Disease	Type of pathogen	Symptoms of disease
Cholera		
Malaria		
TB		
HIV/AIDS		
Smallpox		
Measles		

4. Bacteriophages are viruses that infect bacteria. They can be used to diagnose certain bacterial diseases in much the same way as testing the effect of antibiotics on bacteria. Study the photo below, it shows the effect of a bacteriophage and an antibiotic (polymyxin B) on cholera bacteria.



(a) What evidence is there that the bacteriophage was effective at killing the cholera bacteria?

____

____

____

(b) Was it more or less effective than the antibiotic?

____

(c) How can you tell? ______________________

____

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UNIT 2
Topic 2

Immune Response

Key terms

acquired immunity
active immunity
allergic reaction
antibody (=immunoglobulin)
antigen
B cell (=B lymphocyte)
cell-mediated immunity
clonal selection
complement system
histamine
humoral immunity
immunity
immunological memory
infection
inflammation
interferon
leucocyte
lymphocyte
lysozyme
macrophage
MHC
non-specific defences (=innate immunity)
passive immunity
phagocytosis
primary response
prostaglandins
secondary response
self vs non-self
specific (=adaptive) immune response
T cell (=T lymphocyte)
thymus
vaccination (=immunisation)

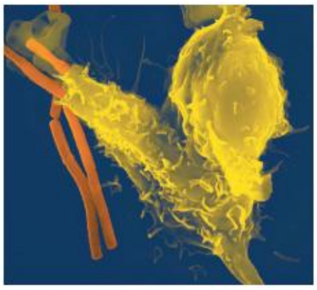
Activity number

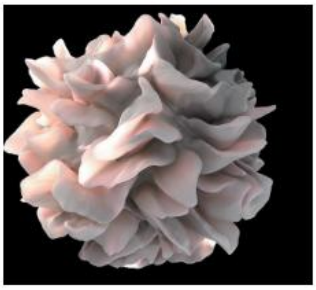
The body's layers of defence

Key skills and knowledge

- ☐ 1 Understand how bacterial and viral pathogens can stimulate the immune system of a host by acting as antigens. Include reference to pathogen surfaces and production of toxins. Explain how the body distinguishes self from non-self, including the role of the major histocompatibility complex (MHC). **175**
- ☐ 2 **SHE** Discuss the factors influencing organ donor suitability, organ transplant, immunosuppression, and rejection. **110 175**
- ☐ 3 Describe the range of physical and chemical defences in animals. Recognise that all plants and animals have innate immune responses (general and non-specific) and that vertebrates also have adaptive (specific) immune responses. **176**
- ☐ 4 Describe non-specific (innate) defences in humans, describing the nature and role of each of the following in protecting against pathogens: **177-179**
  (a) Skin (including sweat and sebum production) and mucous membranes.
  (b) Body secretions (tears, urine, saliva, gastric juice).
  (c) Natural anti-bacterial and anti-viral proteins, e.g. interferon.
  (d) The inflammatory response (prostaglandins, phagocytosis, and vasodilation) and the role of the complement system.
- ☐ 5 Describe passive and active defences in plants, including reference to physical and chemical barriers, cellular defences, and cell death (necrosis). **176**

Volker Brinkmann PLOS cc 2.5





Specific immunity

Key skills and knowledge

- ☐ 6 Explain the specific immune response in vertebrates (e.g. humans), including the role of specificity and memory in the response to antigens. Describe cell-mediated immunity and humoral (antibody-mediated) immunity, identifying the specific white blood cells involved in each case. **180-182 184**
- ☐ 7 Describe clonal selection and the basis of immunological memory. Explain how the immune system is able to respond to the large range of potential antigens. **183**
- ☐ 8 Explain antibody production, including how B cells bring about humoral (antibody-mediated) immunity to specific antigens. **184**
- ☐ 9 Analyse the similarities and differences between passive immunity and active immunity for both naturally acquired and artificially acquired immunity. **185**
- ☐ 10 **SHE** Compare individual and population immunities of different geographical and demographical populations. **185**
- ☐ 11 Explain the principles of vaccination, including reference to the primary and secondary response to infection and the role of these. Explain the role of herd immunity and its relationship to vaccination rate. **186**
- ☐ 12 Interpret long term immune response data. **187**
- ☐ 13 **SHE** Analyse longitudinal health programmes for the prevention and eradication of infectious diseases such as smallpox and influenza.
- ☐ 14 **SHE** Examine short and long term patterns of immunity within the context of vaccination practices and controversies. **188**

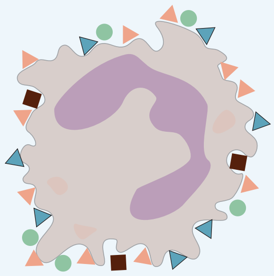
175 The Nature of Antigens

Key Idea: Antigens are substances capable of producing an immune response. It is important that the body can distinguish its own tissues from foreign material so that it does not attack itself.

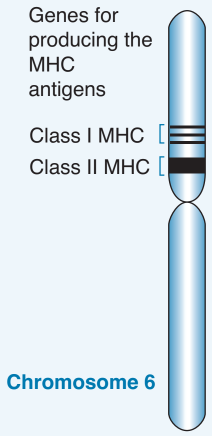
An **antigen** is any substance that produces an immune response. Most antigens are **non-self antigens**, i.e. they are foreign and originate from outside the organism (e.g. bacteria or viruses). Sometimes an organism will react to its own cells and tissues. Antigens that originate from within the body are called **self-antigens**. Normally, because of the development of self-tolerance, the body recognises and does not attack its own tissues. In some instances, the immune system may mistakenly destroy its own tissues. Such a response is called an autoimmune disorder. Allergens are a specific type of antigen, they produce a vigorous hypersensitive allergic response.

Distinguishing self from non-self

- Every type of cell has unique protein markers (antigens) on its surface. The type of antigen varies greatly between cells and between species. The immune system uses these markers to identify its own cells (self) from foreign cells (non-self). If the immune system recognises the antigen markers, it will not attack the cell. If the antigen markers are unknown, the cell is attacked and destroyed.
- In humans, the system responsible for this property is the major histocompatibility complex (**MHC**). The MHC is a cluster of tightly linked genes on chromosome 6. These genes code for protein molecules (MHC antigens) that are attached to the surface of body cells. The main role of MHC antigens is to bind to antigenic fragments and display them on the cell surface so that they can be recognised by the cells of the immune system.
- Class I MHC antigens are found on the surfaces of almost all human cells. Class II MHC antigens occur only on macrophages and B-cells of the immune system.

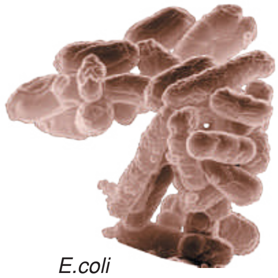


MHC surface proteins (antigens) provide a chemical signature that allows the immune system to recognise the body's own cells



Tolerance towards foreign bodies

- The human body has a very large population of resident microbes. Under normal conditions, *E.coli* in the gut form a protective layer preventing the colonisation of pathogenic bacteria. The microbial cells have foreign antigens but they are not attacked by the immune system because **tolerance** (the prevention of an immune response) has developed.



E.coli

- During pregnancy, specific features of the self recognition system are suppressed to allow the mother to tolerate a nine month relationship with a foreign body (the fetus).

Intolerance to tissue transplants

The MHC is responsible for the rejection of tissue grafts and organ transplants. Foreign MHC molecules on the transplanted tissue are viewed as antigenic, causing the immune system to respond and the tissue to be rejected. To minimise rejection, attempts are made to match the MHC of the organ donor to that of the recipient as closely as possible. Immunosuppressant drugs are also used to minimise the immune response.

Kidney transplant

1. (a) What is an antigen? ______________________________

____

(b) Distinguish between non-self antigens and self antigens: ______________________________

____

____

____

(c) Why is it important that the body detects foreign antigens? ______________________________

____

____

____

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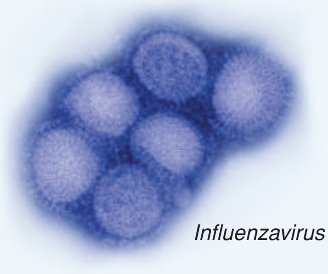
Types of antigens

Non-self antigens

Any foreign material provoking an immune response is termed a non-self antigen. Disease-causing organisms (pathogens) such as bacteria, viruses, and fungi are non-self antigens. The body recognises them as foreign and will attack and destroy them before they cause harm.



CDC

Influenzavirus

Pathogens have ways of avoiding detection. Mutations result in new surface antigens, delaying the immune response and allowing the pathogen to reproduce in its host undetected for a time (e.g. the flu virus, above). Some pathogens, e.g. the malaria-causing *Plasmodium*, switches off its surface antigens in order to enter cells undetected.

Self antigens

The body is usually tolerant of its own antigens. However, sometimes the self-tolerance system fails and the body attacks its own cells and tissues as though they were foreign. This can result in an autoimmune disorder in which tissue is destroyed, grows abnormally, or changes in function.

Autoimmune disorders, such as multiple sclerosis and rheumatoid arthritis, may be triggered by infection. The similarity of the pathogen and self antigens is thought to be behind this failure of self recognition.

Type 1 diabetes is the result of autoimmune destruction of the insulin-producing pancreatic cells. Patients must inject insulin to maintain normal blood glucose levels.

Allergens

Antigens that cause allergic reactions are called allergens. An allergic reaction is a very specific type of immune response in which the immune system overreacts to a normally harmless substance. An allergic response can produce minor symptoms (itching, sneezing, rashes, swelling) or life-threatening anaphylaxis (respiratory and cardiovascular distress).

Common allergens include dust, chemicals, mould, pet hair, food proteins, or pollen grains.

Kent Pryor

The swelling on the foot in the left of the photograph is a result of an allergic reaction to a bee sting.

2. How can pathogens avoid detection by the immune system? ______________________________

____

____

3. (a) What is the nature and purpose of the major histocompatibility complex (MHC)? ______________________________

____

____

____

(b) Why is a self-recognition system important? ______________________________

____

4. (a) What is immune tolerance? ______________________________

____

(b) When might tolerance to foreign antigens be beneficial or necessary? ______________________________

____

____

5. Using examples, describe what happens when the body develops an inappropriate response to:

(a) Self-antigens: ______________________________

____

(b) Normally non-antigenic substances: ______________________________

____

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176 Chemical Defences In Plants and Animals

Key Idea: All plants and animals have chemical defences to defend against pathogens. Some mechanisms are always present while others are stimulated by an attack.

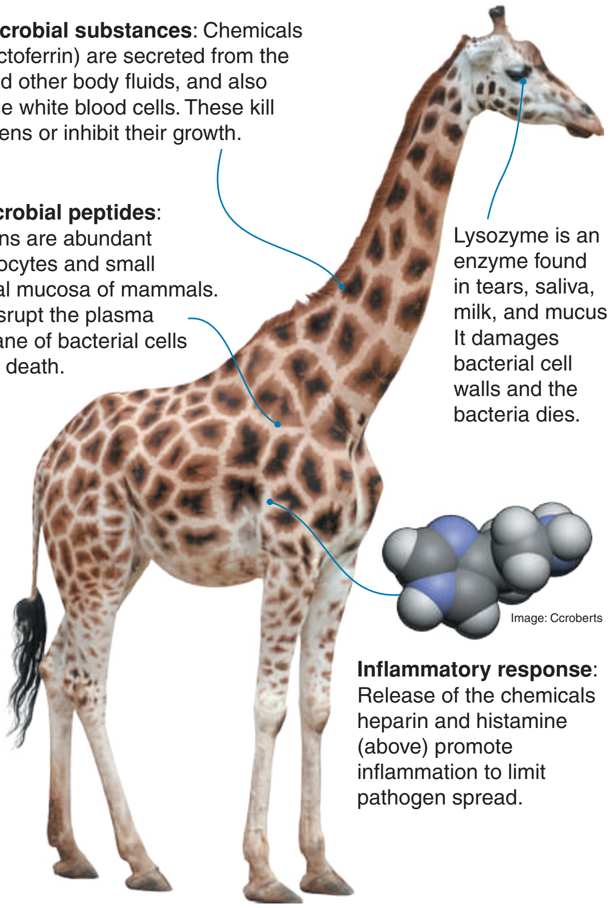
Living organisms are under constant attack from pathogens. As a result plants and animals have evolved a wide range of chemical defences to protect themselves from pathogens and limit the damage they can do. All plants and animals have innate or non-specific defences, whereas vertebrates also have specific immune responses, directed against particular pathogens. The chemical defences of plants not only protect them from attack by pathogens, but may also stop animals eating them or inhibit the growth of other plants.

Chemical defences in animals

Vertebrate innate defences

Antimicrobial substances: Chemicals (e.g. lactoferrin) are secreted from the skin and other body fluids, and also by some white blood cells. These kill pathogens or inhibit their growth.

Antimicrobial peptides: Defensins are abundant in phagocytes and small intestinal mucosa of mammals. They disrupt the plasma membrane of bacterial cells causing death.



Lysozyme is an enzyme found in tears, saliva, milk, and mucus It damages bacterial cell walls and the bacteria dies.

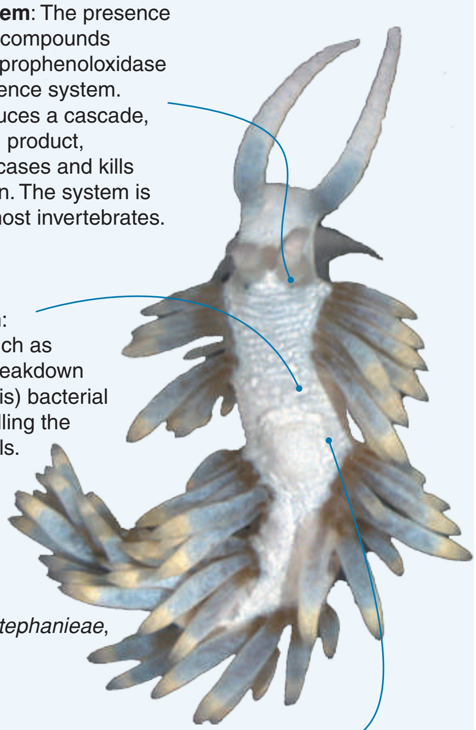
Image: Ccroberts

Inflammatory response: Release of the chemicals heparin and histamine (above) promote inflammation to limit pathogen spread.

Invertebrate innate defences

ProPO system: The presence of microbial compounds initiates the prophenoloxidase (proPO) defence system. proPO produces a cascade, and the final product, melanin, encases and kills the pathogen. The system is present in most invertebrates.

Lytic system: Enzymes such as lysozyme breakdown (by hydrolysis) bacterial cell walls, killing the bacterial cells.



Aeolidiella stephanieae, a sea slug

PHOTO: Kristof A. & Klussmann-Kolb A. cc 2.0

Antimicrobial peptides: The antimicrobial peptide **defensin** binds to the cell membrane of pathogens, and causes damage by puncturing the membrane. The pathogen becomes "leaky" and dies.

1. (a) Describe the advantage of having multiple (non-specific) defence responses: ______________________

____

____

____

(b) Describe a disadvantage of having only general (non-specific) defence responses: ______________________

____

____

2. Compare and contrast the non-specific defences of vertebrate and invertebrate animals: ______________________

____

____

____

____

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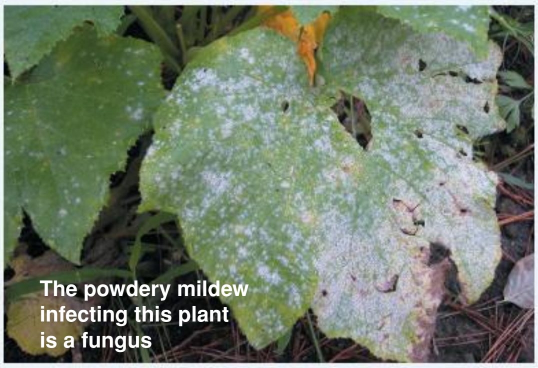
Chemical defences in plants

Passive defences

Passive defences are always present and are not the result of contact with a pathogen or grazer. Plants have both physical and chemical defences to deter pathogens. For example, the thick waxy surface of many leaves (right) acts as a physical barrier to limit pathogen entry. However, if the physical defence is breached, the chemical defences protect the plant against further damage.



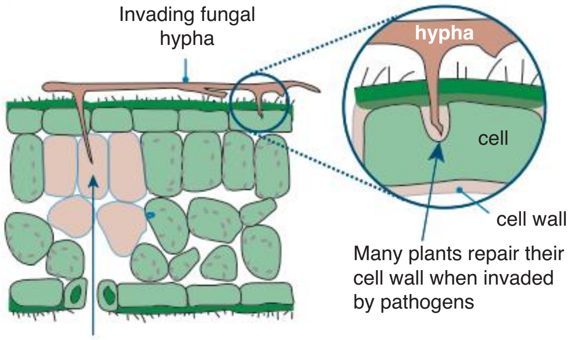
The powdery mildew infecting this plant is a fungus

Many plants produce a range of antimicrobial and antifungal chemicals and enzymes to kill or inhibit the growth of pathogens. Some of these compounds cover the surface of the plant, killing pathogens before they enter the plant. Other compounds act internally.

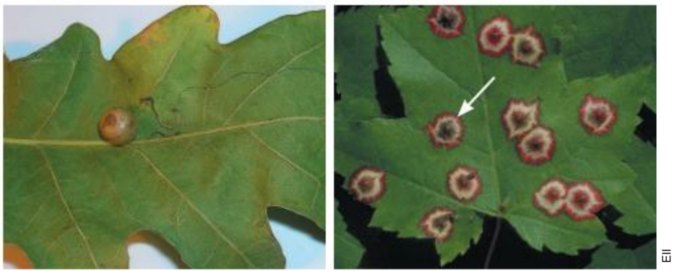
Many herbs have antimicrobial properties. These compounds are sometimes extracted for human use.

Active defences

Once infected, a plant responds actively to prevent any further damage. **Active defences** are invoked only after a pathogen has been recognised, or after wounding or attack by a herbivore. This makes biological sense because active defences are costly to produce and maintain. Active defences work through a variety of mechanisms including slowing pathogen growth, puncturing the cell wall, disrupting metabolism, or killing cells by release of reactive oxygen species such as hydrogen peroxide (H_2O_2).



Many plants produce an enzyme-activated **hypersensitive response** when invaded by pathogens. This leads to the production of reactive nitric oxide and cell death. Cell death in the infected region limits the spread of the pathogen.



Sealing off infected areas gives rise to abnormal swellings called **galls** (oak gall, left and bulls-eye galls on a maple leaf, right). These galls limit the spread of the parasite or the infection in the plant.

3. (a) Distinguish between passive and active defence mechanisms in plants: ______________________

____

____

____

(b) Why are most plant defensive chemicals produced only after a pathogen is detected? ______________________

____

4. How are galls effective in reducing the spread of infection in some plants? ______________________

____

____

5. What similarities are there between the active defence mechanisms of plants and the immune responses of animals?

____

____

____

ISBN: 978-1-927309-83-4

177 The Body's Defences: An Overview

Key Idea: The human body has a tiered system of defences that provides resistance against disease.

The human body has a suite of physical, chemical, and biological defences against pathogens, collectively called **resistance**. The first line of defence consists of external barriers to prevent pathogen entry. If this fails, a second line of defence targets any foreign bodies that enter. Lastly, the specific immune response provides targeted defence against the pathogen. The defence responses of the body fall into two broad categories, the innate and the adaptive immune responses. The **innate** (or non-specific) response (the first and second lines of defence) protects against a broad range of non-specific pathogens. This response is present in all animals. It involves blood proteins (e.g. complement), inflammation, and phagocytic white blood cells. The **adaptive** (or specific) immune response (the third line of defence) is specific to identified pathogens and is present only in vertebrates. It involves defence by specific T cells (cellular immunity) as well as antibodies, which neutralise foreign antigens (humoral immunity).

1st line of defence

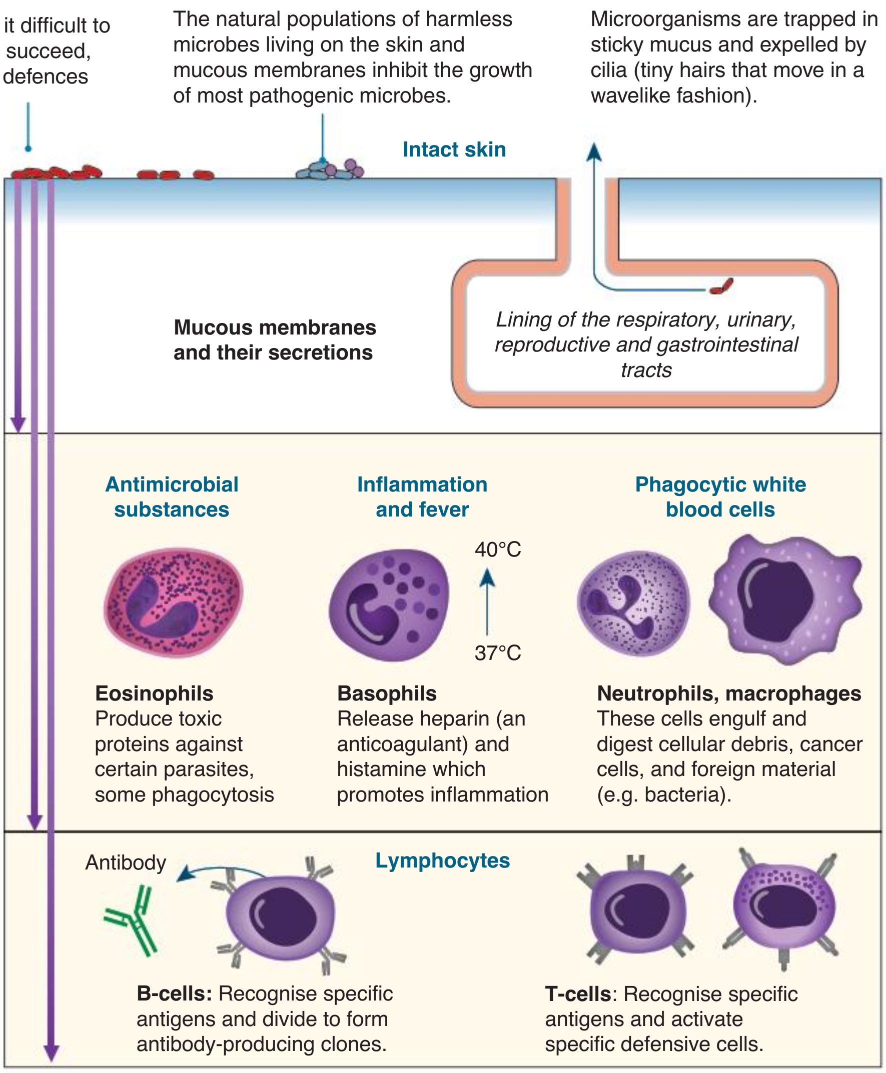
The skin provides a physical barrier to the entry of pathogens. Healthy skin is rarely penetrated by microorganisms. Its low pH is unfavourable to the growth of many bacteria and its chemical secretions (e.g. sebum, antimicrobial peptides) inhibit growth of bacteria and fungi. Tears, mucus, and saliva also help to wash bacteria away.

2nd line of defence

A range of defence mechanisms operate inside the body to inhibit or destroy pathogens. These responses react to the presence of any pathogen, regardless of which species it is. White blood cells are involved in most of these responses. It includes the complement system whereby blood plasma proteins work together to bind pathogens and induce inflammation to help fight infection.

3rd line of defence

Once the pathogen has been identified by the immune system, **lymphocytes** (specialised white blood cells) launch a range of specific responses to the pathogen, including the production of defensive proteins called **antibodies**. Each type of antibody is produced by a B-cell clone and is specific against a particular antigen.



1. What are the differences between the innate and adaptive immune responses: ______________________

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2. How does having a tiered defence help protect an organism from a pathogen? ______________________

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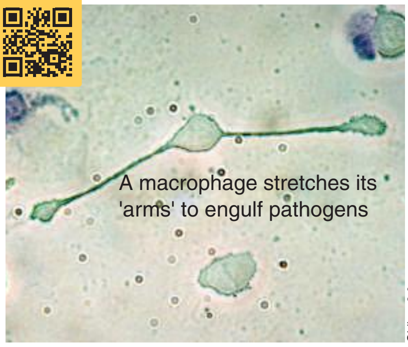
178 The Innate Immune Response

Key Idea: The innate immune response provides a rapid response to contain and destroy pathogens. Inflammation is an important part of the response.

The innate immune system provides protection against a pathogen, even if it has never encountered it before. The innate response is very fast and provides general protection (it is not antigen specific), but does not provide long lasting immunity. Many different cells and processes are involved. The primary outcome is to destroy and remove the cause of infection. This is achieved through containing the infection through inflammation and then recruitment of immune cells to destroy the pathogen. During this process a series of biochemical reactions (the complement system) are activated to destroy the pathogen and recruit immune cells to the site.

Phagocytic cells of the innate immune system



A macrophage stretches its 'arms' to engulf pathogens

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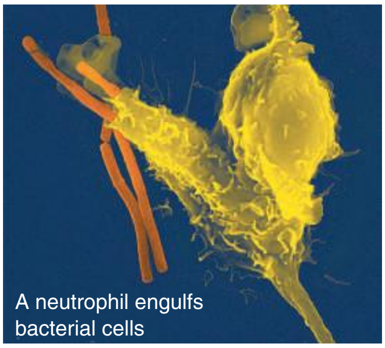
Macrophage

Macrophages are very large and are highly efficient phagocytes. They are found throughout the body and move using an amoeboid movement (above) to hunt down and destroy pathogens. Macrophages also have a role in recruiting other immune cells to an infection site.

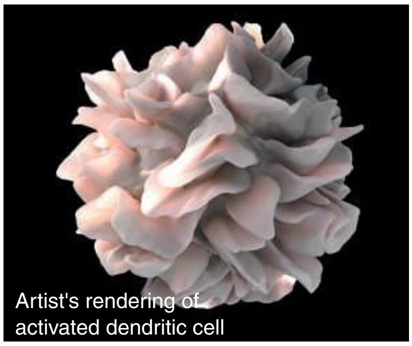


A neutrophil engulfs bacterial cells

Volker Brinkmann PLOS cc 2.5

Neutrophil

Neutrophils are the most abundant type of phagocyte and are usually the first cells to arrive at the site of an infection. They contain toxic substances that kill or inhibit the growth of bacteria and fungal pathogens. Neutrophils release cytokines which amplify the immune response and recruit other cells to the infection site.

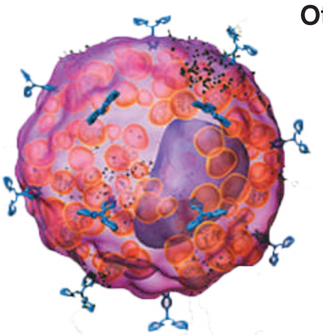


Artist's rendering of activated dendritic cell

Dendritic cell

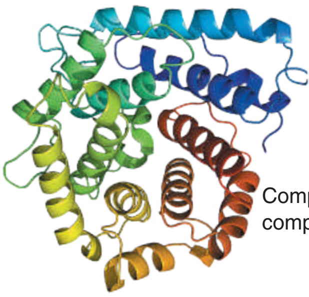
Dendritic cells are present in tissue that are in contact with the external environment (e.g. skin, and linings of the nose, lungs, and digestive tract). They act as messengers between the innate and adaptive immune system by presenting antigen materials to the T cells of the immune system.

Other cells and processes of the innate immune response



Mast cells

Mast cells contain a lot of histamine, a chemical involved in both inflammation and allergic responses. When activated, histamine is released from the mast cell causing the blood vessels to dilate and become leaky. The increased permeability allows phagocytes to reach the site of infection.



Complement component 3 (C3)

Complement proteins

The complement system comprises a number of different proteins. The proteins circulate as inactive precursors until they are activated. Complement proteins have three main roles: phagocytosis, attracting macrophages and neutrophils to the infection site, and rupturing the membranes of foreign cells.

The process of inflammation

The inflammatory process is a protective response to pathogen invasion. It has several functions: (1) to destroy the cause of the infection and remove it and its products from the body; (2) if this fails, to limit the effects on the body by confining the infection to a small area; (3) replacing or repairing tissue damaged by the infection.

1. Outline the role of the following phagocytes in the innate immune response:

   (a) Macrophages: ____________________

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   (b) Neutrophils: ____________________

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   (c) Dendritic cells: ____________________

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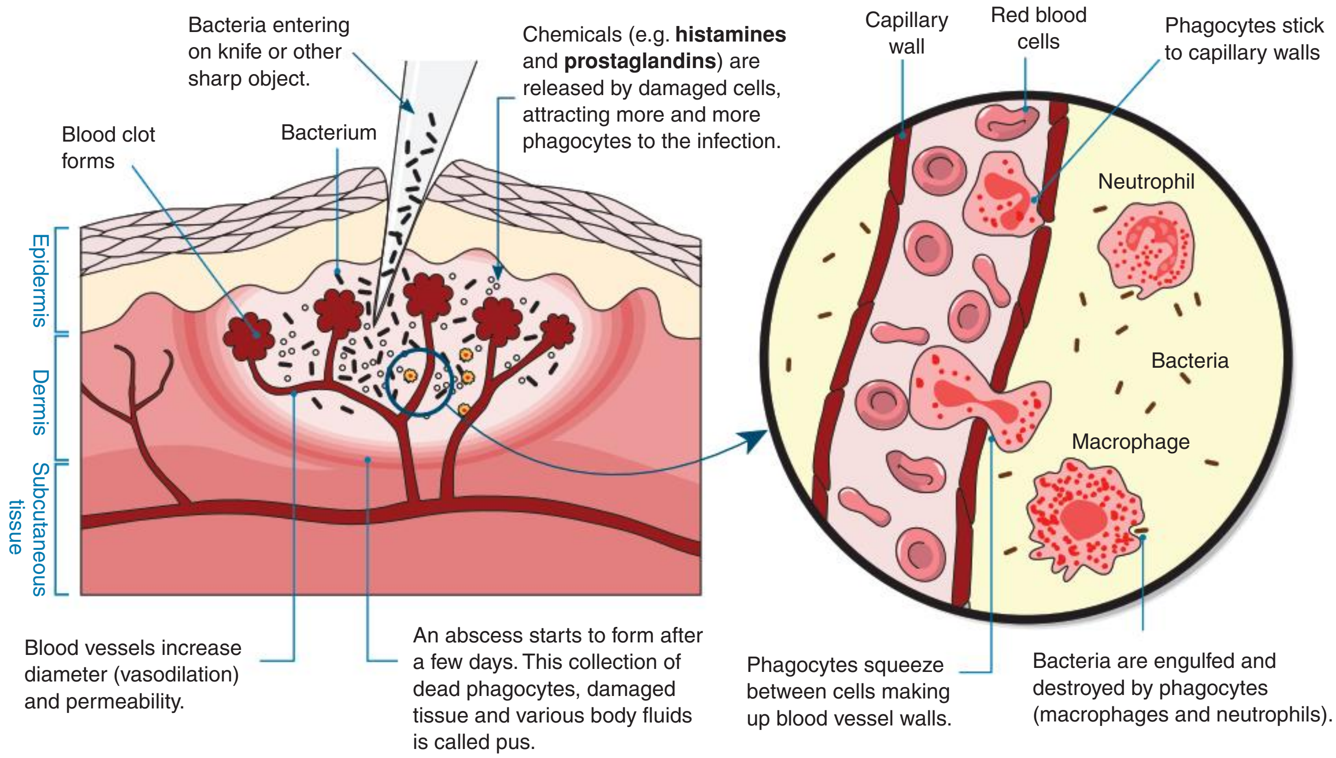
The inflammatory response



Stages in the inflammatory response

Increased diameter and permeability of blood vessels
Blood vessels increase their diameter and permeability in the area of damage. This increases blood flow to the area and allows defensive substances to leak into tissue spaces.

Phagocyte migration and phagocytosis
Within one hour of injury, phagocytes appear on the scene. They squeeze between cells of blood vessel walls to reach the damaged area where they destroy invading microbes.

Tissue repair
Functioning cells or supporting connective cells create new tissue to replace dead or damaged cells. Some tissue regenerates easily (skin) while others do not at all (cardiac muscle).

2. What role does the complement system play in immunity? ____________________

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3. Outline the three stages of inflammation and identify the beneficial role of each stage:

(a) ____________________

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(b) ____________________

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(c) ____________________

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4. What role do mast cells play in inflammation? ____________________

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5. Why does pus form at the site of infection? ____________________

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179 Phagocytes and Phagocytosis

Key Idea: Phagocytes are mobile white blood cells that ingest microbes and digest them by phagocytosis.

Phagocytosis is the process by which a cell engulfs another cell or particle. Cells which do this are called phagocytes. All types of phagocytes (e.g. neutrophils, dendritic cells, and macrophages) are white blood cells. These specialised cells have receptors on their surfaces that can detect antigenic material, such as microbes. They then ingest the microbes and digest them by phagocytosis. As well as destroying microbes, phagocytes also release substances called cytokines that help to coordinate the overall response to an infection. Macrophages and dendritic cells also play a role in antigen presentation in processing and presenting antigens from ingested microbes to other cells of the immune system.

1. **Detection and interaction**
Microbe coated in chemical markers is detected by the phagocyte, which attaches to it. Chemical markers coating the foreign material (e.g. a bacterial cell), mark it as a target for phagocytosis.

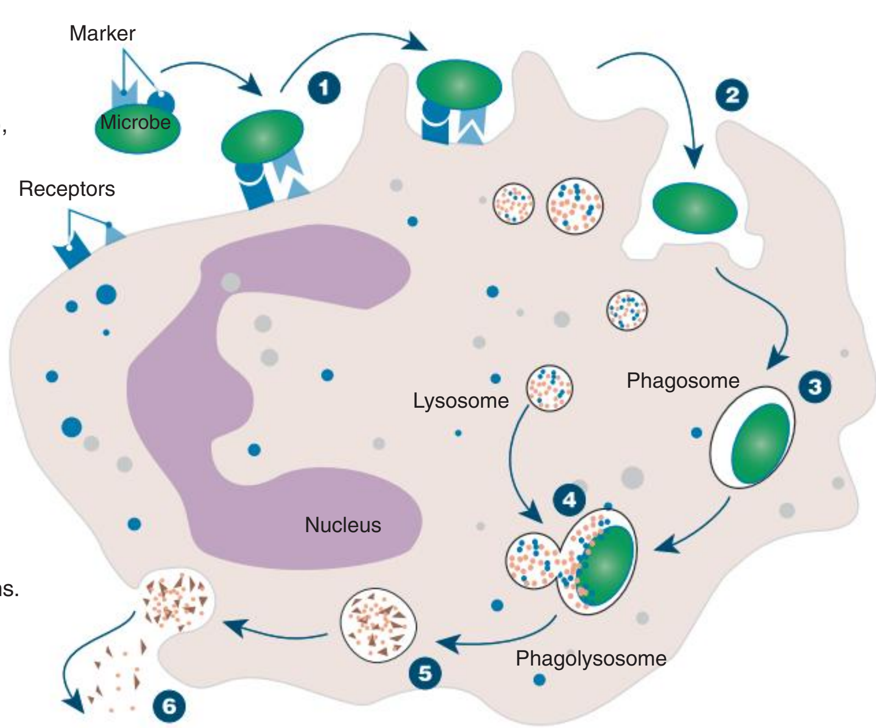
2. **Engulfment**
The markers trigger engulfment of the microbe by the phagocyte. The microbe is taken in by endocytosis.

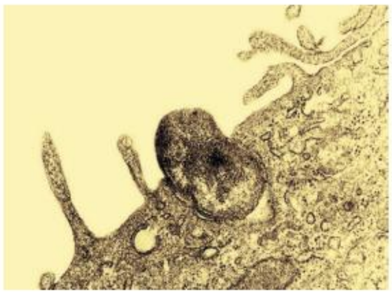
3. **Phagosome forms**
A phagosome forms, enclosing the microbe in a membrane.

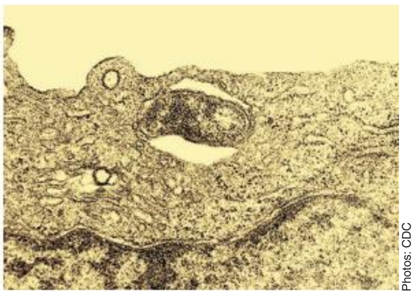
4. **Fusion with lysosome**
Phagosome fuses with a lysosome containing powerful antimicrobial proteins. The fusion forms a phagolysosome.

5. **Digestion**
The microbe is broken down into its chemical constituents.

6. **Discharge**
Indigestible material is discharged from the phagocyte.







Photos right: A cell ingests and engulfs a bacterium by phagocytosis.

1. Identify the white blood cells capable of phagocytosis: ___________________________

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2. Explain the role of chemical markers and phagocyte receptors in enhancing phagocytosis: ___________________________

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3. What is the purpose of phagocytosis and how is involved in internal defence? ___________________________

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180 Processing Antigens

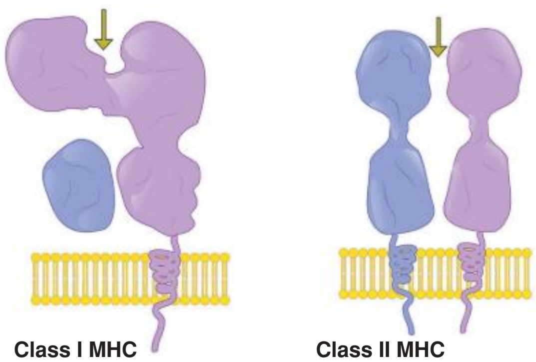
Key Idea: Antigen processing prepares and displays antigens for presentation to the T-cells of the immune system.

Antigen presenting cells (APCs) process and present antigens for recognition by T-cells. During antigen processing, the APC digests the foreign antigen into smaller peptide fragments. These fragments are then displayed on the surface of the APC by MHC receptors. The immune response evoked by the T-cells depends on which MHC receptor (MHCI or MHCII) is activated. Antigen presentation is necessary for T-cells to recognise infection or abnormal growth and activate other cells of the immune system. Dendritic cells, macrophages, and B-cells are APCs.

The role of MHC receptors

Recall there are two types of MHC receptors, class I and class II (right). Both have similar functions in that they display antigens on cell surfaces so that they can be recognised and processed by the T-cells of the immune system. T-cells can only recognise antigens if they are displayed by the MHC receptors. MHC receptors presenting no foreign antigens are ignored by T-cells, and are recognised as "self". Only MHC receptors with foreign antigens bound to them will attract T-cells and evoke an immune response.

The two classes of MHC receptors display different types of antigens. Class I MHC receptors display antigens from intracellular pathogens (e.g. viruses). Class II MHC receptors display antigens from pathogens that have been phagocytosed (e.g. bacteria).



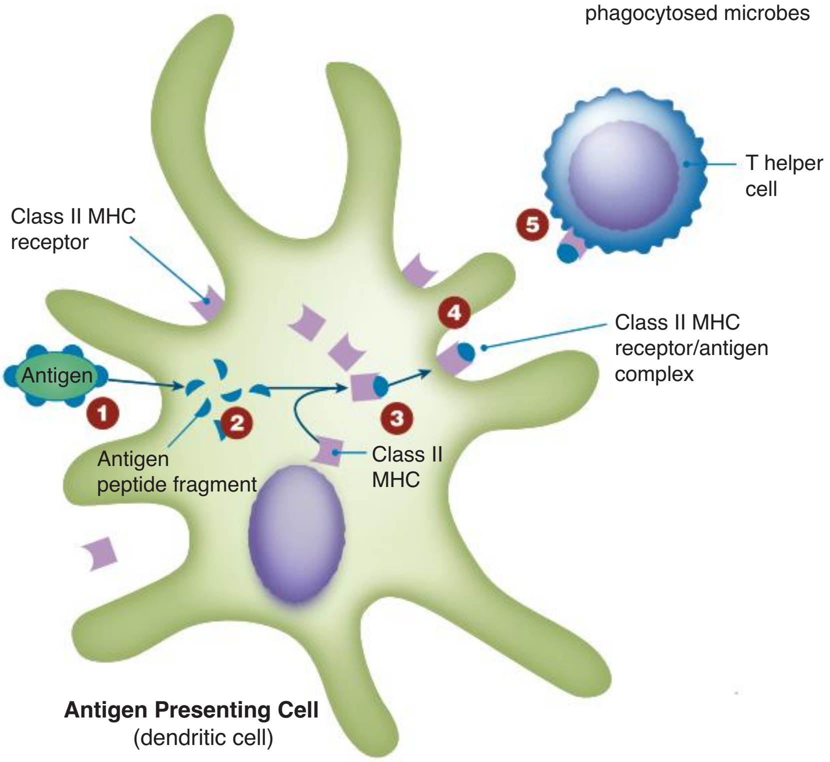
Class I MHC
Antigens from within the cell, e.g. viral proteins

Class II MHC
Antigens from outside the cell, e.g. proteins from phagocytosed microbes

An overview of antigen processing

The diagram on the right represents antigen processing of an extracellular peptide antigen via a class II MHC receptor.

1. An APC encounters an antigen.
2. The antigen is engulfed via phagocytosis and digested into short peptide fragments.
3. Class II MHC receptors bind the fragments and form a MHC-antigen complex.
4. The MHC-antigen complex is displayed on the surface of the APC.
5. A receptor on the T helper cell recognises the peptide as foreign. It binds and a series of events stimulate the adaptive immune response.



Antigen Presenting Cell
(dendritic cell)

1. What is the purpose of antigen processing? ______________________________

2. Why do MHC receptors with no antigenic peptide bound not cause an immune response? ______________________________

3. Describe the differences between class I and class II MHC receptors: ______________________________

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181 The Lymphatic System

Key Idea: Defensive white blood cells are transported in lymph through the lymphatic system and are concentrated in the lymph nodes.

The lymphatic system is a network of tissues and organs that collects the tissue fluid leaked from the blood vessels and returns it to the heart. The lymphatic system has an important role in immunity because the fluid transported around the body by the lymphatic system (lymph) is rich in infection-fighting white blood cells. The thymus is a primary lymphoid organ and the site of T cell maturation. Secondary lymphoid tissues (spleen and lymph nodes) are important as the site of lymphocyte (T and B cell) activation.

Tonsils
A collection of secondary lymphoid tissues in the throat. They provide defence against ingested or inhaled pathogens and produce activated B and T cells.

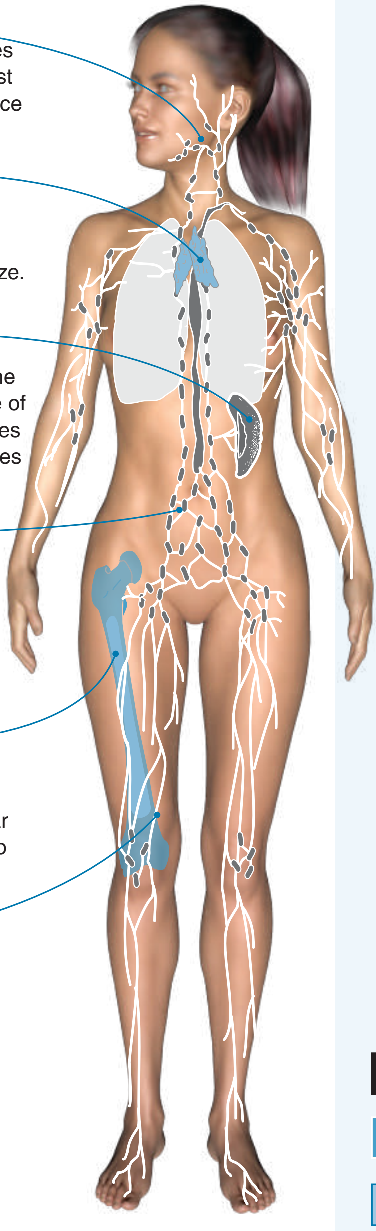
Thymus
A primary lymphoid organ located above the heart. It is large in infants and shrinks after puberty to a fraction of its original size. Important for maturation of **T-cells**.

Spleen
The largest mass of lymphatic tissue in the body. It stores and releases blood in case of demand (e.g. in severe bleeding), produces mature B-cells and antibodies and removes antibody-coated antigenic material.

Lymph nodes
Ovoid masses of lymph tissue where lymphocytes are concentrated. Each node receives lymph through several narrow afferent (entry) vessels and exits via wider efferent (exit) vessels.

Red bone marrow
A primary lymphoid tissue where all the different kinds of blood cells (including white blood cells) are produced by cellular differentiation from stem cells. B cells also mature here.

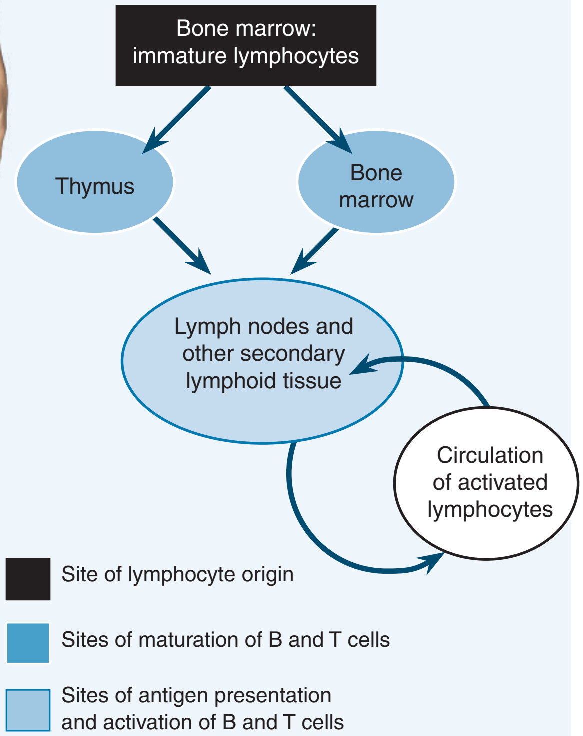
Lymphatic vessels
When the fluid leaking from capillaries is picked up by lymph capillaries, it is called **lymph**. The lymph, carrying leukocytes, flows in lymphatic vessels through the secondary lymphoid tissues.



The lymphatic system and immunity

The fluid circulating through the lymphatic system passes through the secondary lymphoid tissues, including the **lymph nodes**. These are ovoid organs, which are present throughout the lymphatic system. Lymph nodes receive lymph via incoming (afferent) vessels and are the site of lymphocyte activation.

Lymphocytes in circulation are constantly moving between sites where antigens may be encountered. These antigens are presented to T cells in the secondary lymphoid tissues. Recognition of the antigen leads to activation and proliferation of both T and B cells, vastly increasing the number of lymphocytes. After several days, antigen-activated lymphocytes begin leaving the lymphoid tissue.



1. What is the general role of the lymphatic system in immunity? ______________________

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2. (a) What is the role of the secondary lymphoid tissue, e.g. lymph nodes, in the immune response? ______________________

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(b) Why do you think lymph nodes become swollen when someone has an infection? ______________________

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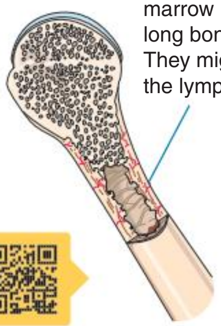
182 The Adaptive Immune System

Key Idea: Antigens, such as the cell walls of microbial cells, when processed by antigen-presenting cells, activate the B and T cells of the immune system against specific pathogens.

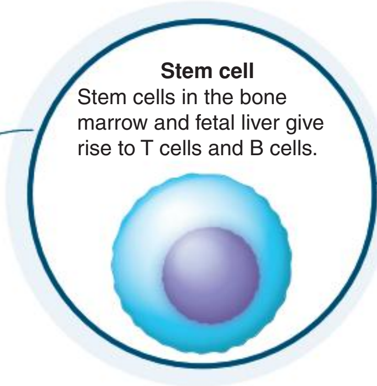
There are two main components of the adaptive immune system: the humoral and the cell-mediated responses. They work separately and together to protect against disease. The **humoral immune response** is associated with the serum (the non-cellular part of the blood) and involves the action of antibodies secreted by B cells (B lymphocytes). Antibodies are found in extracellular fluids including lymph, plasma, and mucus secretions and protect against viruses, and bacteria and their toxins. The **cell-mediated immune response** is associated with the production of specialised lymphocytes called **T cells**. Antigens are recognised by T cells only after antigen processing. The antigen is first engulfed by an antigen-presenting cell, which processes the antigen and presents it on its surface. T helper cells can then recognise the antigen and activate other cells of the immune system.

Lymphocyles and their functions

Bone marrow
B cells mature in the bone marrow in the shaft of the long bones (e.g. the femur). They migrate from here to the lymphatic organs.

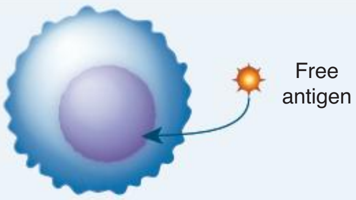


Stem cell
Stem cells in the bone marrow and fetal liver give rise to T cells and B cells.



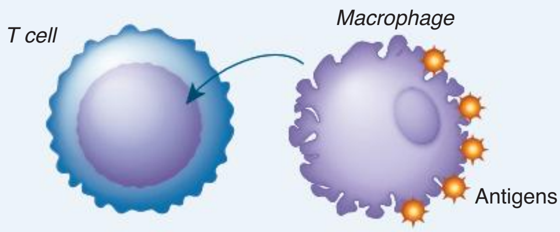
Thymus gland
The thymus gland is located above the heart. It is large in infants but becomes smaller with age. Immature T cells move to the thymus to mature before migrating to other lymphatic organs.

B CELLS



B cells recognise and bind antigens. Each B cell recognises one specific antigen. Helper T cells recognise specific antigens on B cell surfaces and induce their maturation and proliferation. A mature B cell may carry as many as 100,000 antigenic receptors embedded in its surface membrane. B cells defend against bacteria and viruses outside the cell and toxins produced by bacteria (free antigens).

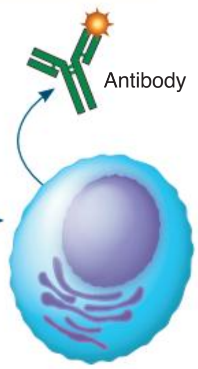
T CELLS



T cells respond only to antigen fragments that have been processed and presented by specialised antigen-presenting cells (dendritic cells and macrophages). They defend against:

- Intracellular bacteria and viruses
- Protozoa, fungi, flatworms, and roundworms
- Cancerous cells and transplanted foreign tissue

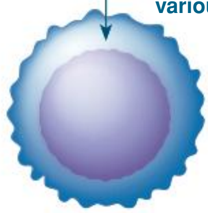
Differentiate into two kinds of cells

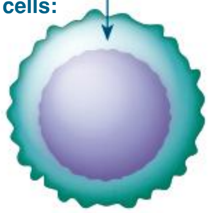


Memory cells
Some B cells differentiate into long-lived memory cells (see Clonal Selection). When these cells encounter the same antigen again (even years or decades later), they rapidly differentiate into antibody-producing plasma cells.

Plasma cells
When stimulated by an antigen (see Clonal Selection), some B cells differentiate into plasma cells, which secrete **antibodies** into the bloodstream. The antibodies then inactivate the circulating antigens.

Differentiate into various kinds of cells:





T helper cell activates T killer cells and other helper T cells. They are needed for B cell activation.

T killer cell destroys target cells on contact. Recognises tumour or virus-infected cells by their surface markers. They are also called cytotoxic T cells.

There are also other types of T cells:
T memory cells have encountered specific antigens before and can respond quickly and strongly when the same antigen is encountered again.
T regulator cells control the immune response by turning it off when no more antigen is present. They are important in the development of self tolerance.

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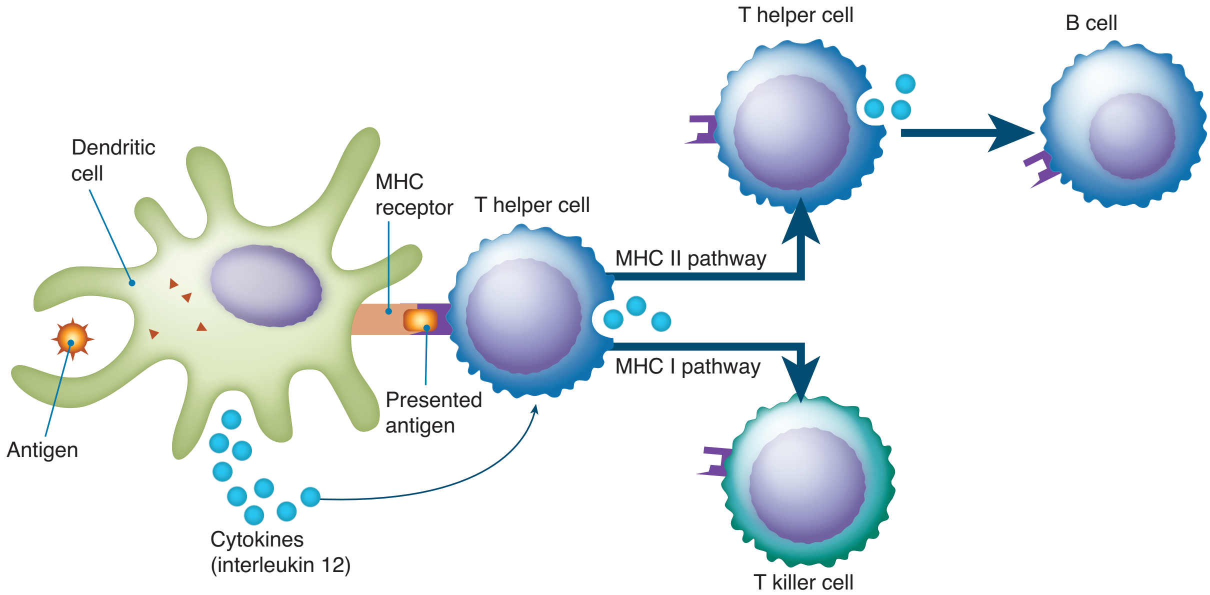
Dendritic cells stimulate the activation and proliferation of lymphocytes



- Dendritic cells (DC) are antigen-presenting cells. Immature DC originate in bone marrow and migrate through the body to lymph nodes. When a DC encounters an antigen, it presents it to a T helper cell, stimulating it to secrete chemicals called cytokines. Cytokines stimulate the activation and proliferation (rapid increase in number) of T cells, activating the immune system against that specific antigen. T helper cells go on to stimulate the production of antibody-producing B cells.
- Dendritic cells with MHC I receptors stimulate the production of T killer cells.
- Dendritic cells with MHC II receptors stimulate the production of T helper cells.

1. Where do B cells and T cells originate (before maturing)? ______________________

2. (a) Where do B cells mature? ______________________

   (b) Where do T cells mature? ______________________

3. Describe the nature and general action of the two major divisions in the immune system:

   (a) Humoral immune system: ______________________

   (b) Cell-mediated immune system: ______________________

4. Explain how an antigen causes the activation and proliferation of T cells and B cells, including the role of dendritic cells:

5. In what way do dendritic cells act as messengers between the innate and the adaptive immune systems?

6. Describe the function of each of the following cells in the immune system response:

   (a) T helper cells: ______________________

   (b) T killer cells: ______________________

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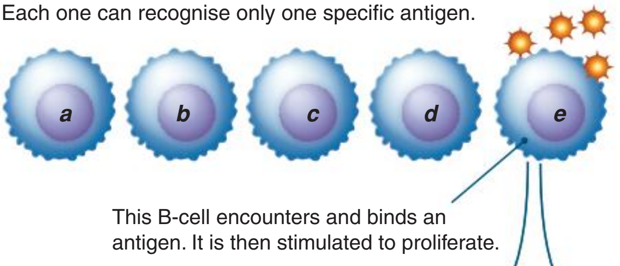
183 Clonal Selection

Key Idea: Clonal selection theory explains how lymphocytes can respond to a large and unpredictable range of antigens.

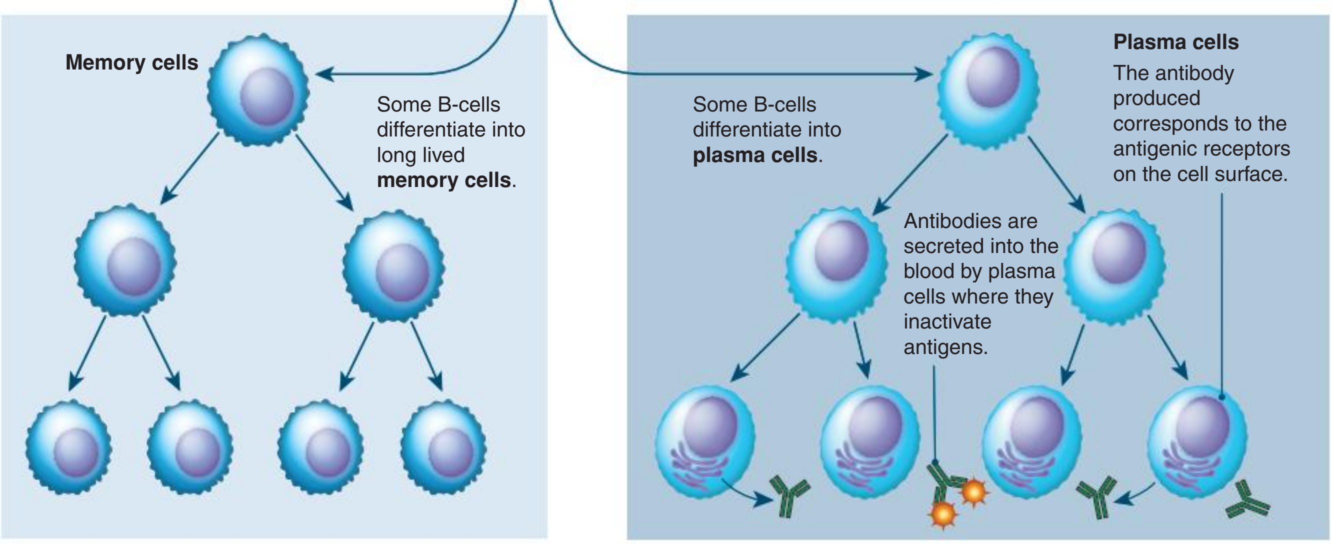
The **clonal selection theory** explains how the immune system can respond to the large and unpredictable range of potential antigens in the environment. The diagram below describes clonal selection after antigen exposure for B cells. In the same way, a T cell stimulated by a specific antigen will multiply and develop into different types of T cells. Clonal selection and differentiation of lymphocytes provide the basis for **immunological memory.**

Five (a-e) of the many B cells generated during development. Each one can recognise only one specific antigen.



Clonal selection theory

Millions of B cells form during development. Antigen recognition is randomly generated, so collectively they can recognise many antigens, including those that have never been encountered. Each B cell has receptors on its surface for specific antigens and produces antibodies that correspond to these receptors. When a B cell encounters its antigen, it responds by proliferating and producing many clones that produce the same kind of antibody. This is called clonal selection because the antigen selects the B cells that will proliferate.



Some B cells differentiate into long lived **memory cells**. These are retained in the lymph nodes to provide future immunity (**immunological memory**). If the antigen returns a second time, memory B cells react more quickly and vigorously than the first time the antigen appeared.

Plasma cells secrete antibodies specific to the antigen that stimulated their development. Each plasma cell lives for only a few days, but can produce about 2000 antibody molecules per second. During development, any B cells that react to the body's own antigens are destroyed in a process that leads to **self tolerance** (acceptance of the body's own tissues).

1. Describe how clonal selection results in the proliferation of one particular B cell clone: ______________________

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2. (a) What is the function of the plasma cells in the immune system response? ______________________

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(b) What is the significance of B cells producing antibodies that correspond to (match) their antigenic receptors?

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3. (a) Explain the basis of immunological memory: ______________________

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(b) Why are B memory cells able to respond so rapidly to an encounter with an antigen long after an initial infection?

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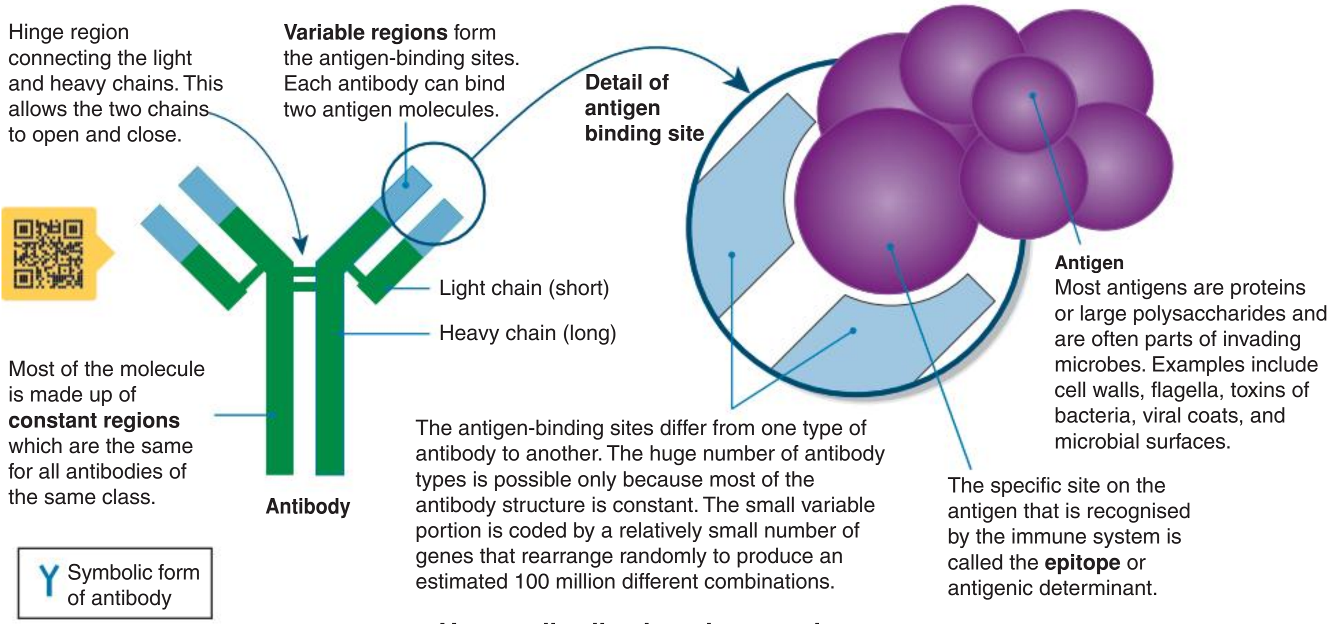
184 Antibodies

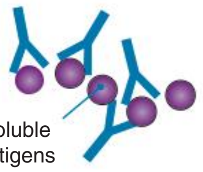
Key Idea: Antibodies are large, Y-shaped proteins, made by plasma cells, which destroy specific antigens.

Antibodies and antigens play key roles in the response of the immune system. **Antigens** are foreign molecules which promote a specific immune response. Antigens include pathogenic microbes and their toxins, as well as substances such as pollen grains, blood cell surface molecules, and the surface proteins on transplanted tissues. **Antibodies** (or immunoglobulins) are proteins made in response to antigens. They are secreted from B cells into the plasma where they can recognise, bind to, and help destroy antigens. There are five classes of antibodies, each plays a different role in the immune response. Each type of antibody is specific to only one particular antigen.



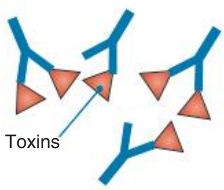
How antibodies inactivate antigens

Acting as agglutinins



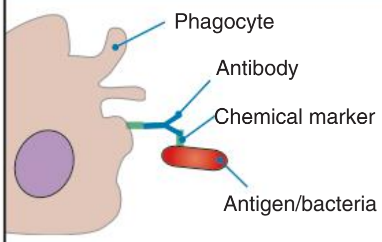
Antibodies can act as agglutinins and cause antigens to bind together, forming inactivated clumps.

Acting as antitoxins



Antibodies can act as antitoxins by binding to toxins and neutralising them.

Enhancing phagocytosis



Tags foreign cells for destruction by phagocytes.

1. Describe the structure of an antibody, identifying the specific features of its structure that contribute to its function:

2. Explain how the following actions by antibodies enhance the immune system's ability to stop infections:

(a) Acting as agglutinins:

(b) Acting as antitoxins:

(c) Tagging foreign cells with chemical markers:

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185 Acquired Immunity

Key Idea: Acquired immunity is a resistance to specific pathogens acquired over the life-time of an organism.

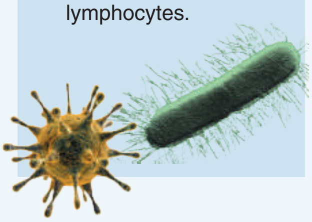
We are born with natural or **innate resistance** which provides non-specific immunity to certain illnesses. In contrast, **acquired immunity** is protection developed over time to specific antigens. **Active immunity** develops after the immune system responds to being exposed to microbes or foreign substances. **Passive immunity** is acquired from gaining preformed antibodies without exposure to the antigen. Immunity can be naturally acquired, through natural exposure to microbes, or artificially acquired as a result of medical treatment (below).

Acquired immunity

Naturally acquired

Active

Antigens enter the body naturally:
- Microbes cause the person to actually catch the disease
- Sub-clinical infections (those that produce no evident symptoms).
- The body produces antibodies and specialised lymphocytes.



Passive

Antibodies pass from the mother to the fetus via the placenta during pregnancy, or to her infant through her breast milk.
The infant's body does not produce any antibodies of its own.

Artificially acquired

Active

Antigens (non-infectious parts of microbes) are introduced in **vaccines** (a process called **vaccination**). The body produces antibodies and specialised lymphocytes and becomes **immunised**.

Passive

Pre-formed antibodies in an **immune serum** are introduced into the body by injection (e.g. antivenom used to treat snake bites).
The body does not produce antibodies.

1. (a) What is meant by passive immunity? ______________________________

   (b) Distinguish between naturally and artificially acquired passive immunity and give an example of each: ______________________________

2. (a) Why does a newborn baby need to have received a supply of maternal antibodies prior to birth? ______________________________

   (b) Why is this supply supplemented by antibodies in breast milk? ______________________________

3. (a) What is active immunity? ______________________________

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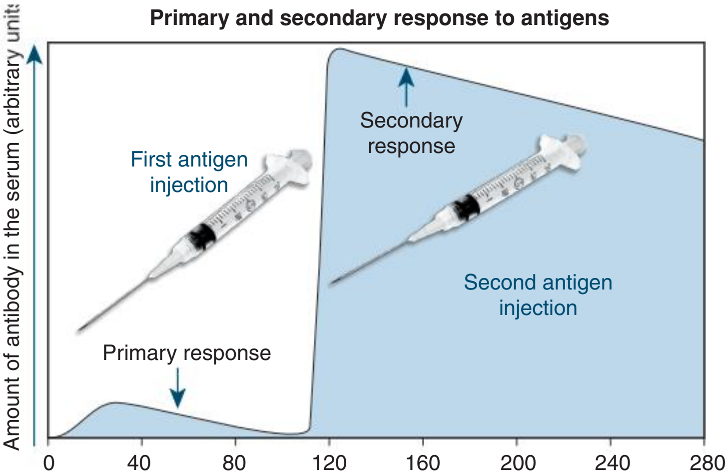
Primary and secondary response to antigens

When the B cells encounter antigens and produce antibodies, the body develops active immunity against that antigen.

The initial response to antigenic stimulation, caused by the sudden increase in B cell clones, is called the primary response. Antibody levels as a result of the primary response peak a few weeks after the response begins and then decline. However, because the immune system develops an immunological memory of that antigen, it responds much more quickly and strongly when presented with the same antigen subsequently (the secondary response).

This forms the basis of immunisation programmes where one or more booster shots are provided following the initial vaccination.



(b) Distinguish between naturally and artificially acquired active immunity and give an example of each: _______________

____

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____

4. (a) Describe two differences between the primary and secondary responses to presentation of an antigen: _______________

____

____

____

(b) Why is the secondary response so different from the primary response? _______________

____

____

____

5. Some diseases do not affect all members of a population equally. Socioeconomic factors, age, sex, ethnicity and where someone lives can influence how a disease affects a particular individual or population. The data (right) shows deaths from influenza (flu) in Australia by age over three years.

(a) Do you think the data shows an age related effect for influenza deaths? Explain your reasoning:

____

____

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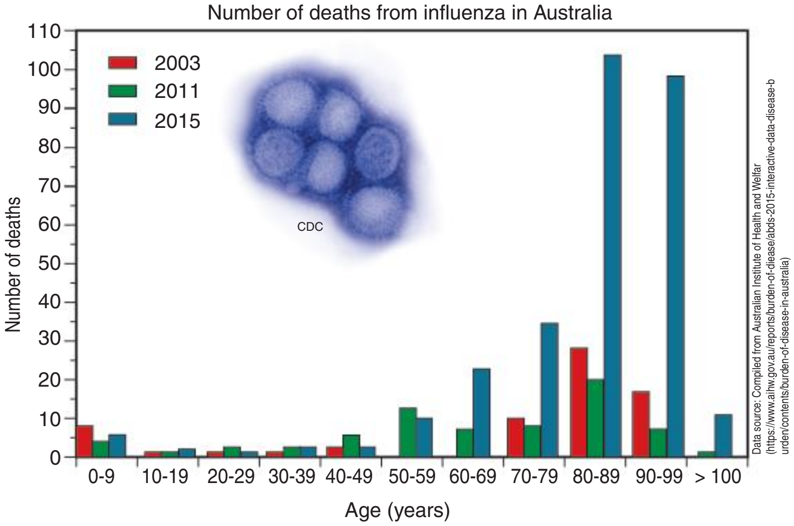

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(b) Suggest what could be done to help reduce the number of influenza deaths: _______________

____

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186 Vaccines and Vaccination

Key Idea: A vaccine is a suspension of antigens that is deliberately introduced into the body to protect against disease. If enough of the population are vaccinated, herd immunity provides protection to unvaccinated individuals.

A **vaccine** is a preparation of a harmless foreign antigen that is deliberately introduced into the body to protect against a specific disease. The antigen in the vaccine is usually some part of the pathogen and it triggers the immune system to produce antibodies against the antigen, but it does not cause the disease. The immune system remembers its response and will produce the same antibodies if it encounters the antigen again. If enough of the population are vaccinated, herd immunity (indirect protection) provides unvaccinated individuals in the population with a measure of protection against the disease. There are two basic types of vaccine, subunit vaccines and whole-agent vaccines (below).

Types of Vaccine

Whole-agent vaccine

Contains whole, non-virulent microorganisms

Inactivated (killed)

Viruses for vaccines may be inactivated with formalin or other chemicals. They present almost no risk of infection, e.g. most influenza vaccines, Salk polio vaccine.

Attenuated (weakened)

Attenuated viruses are usually strains in which mutations have accumulated during culture. These live viruses can back-mutate to a virulent form, e.g. MMR vaccine.

Subunit vaccine

Contains some part or product of microbes that can produce an immune response. Includes vaccines made using genetic engineering, inactivated toxins, and conjugated and **acellular vaccines**, e.g. the diphtheria-tetanus-pertussis vaccine and the vaccine against bacterial meningitis.

Why are vaccinations given?

CDC

Vaccines against common diseases are given at various stages during childhood according to an immunisation schedule. Vaccination has been behind the decline of some once-common childhood diseases, such as mumps and measles.

CDC

Most vaccinations are given in childhood, but adults may be vaccinated against a disease (e.g. TB, tetanus) if they are in a high risk group (e.g. the elderly or farmers) or to provide protection against seasonal diseases such as influenza.

Tourists may need specific vaccines if the country they are visiting has a high incidence of a certain disease. For example, travellers to South America should be immunised against yellow fever, a disease that does not occur in Australia.

1. (a) What is a vaccine? ______________________________

____

(b) Provide some examples of when vaccinations are needed: ______________________________

____

____

____

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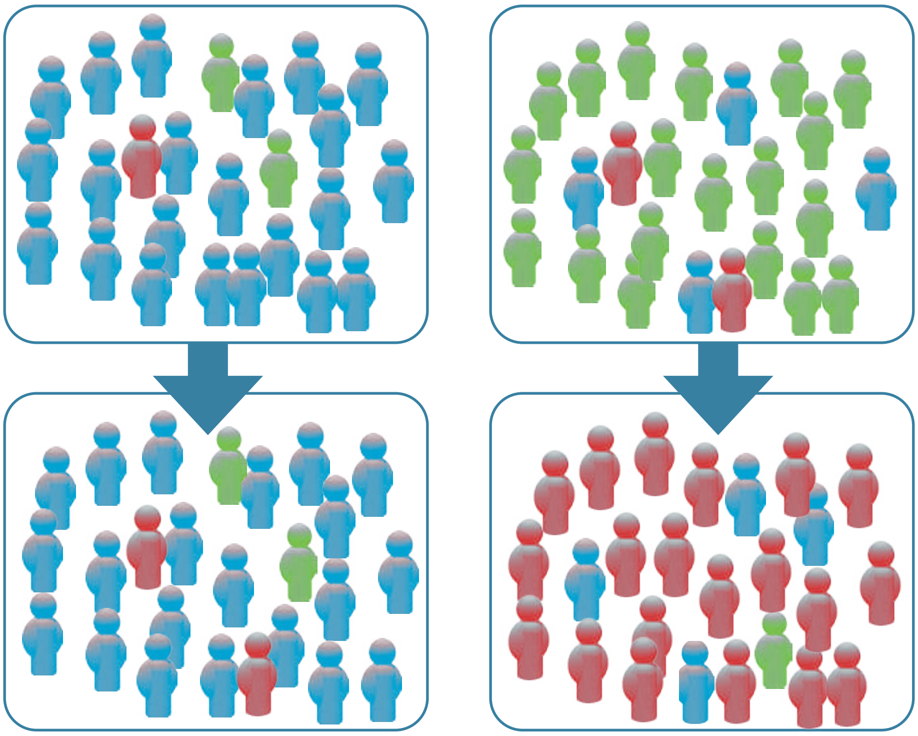
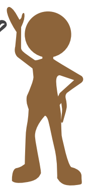
Vaccination can provide herd immunity

Herd immunity occurs when the vaccination of a significant portion of a population provides some protection for individuals who have not developed immunity (e.g. have not been vaccinated and are not immunised). In order to be effective for any particular disease, a high percentage of the population needs to be vaccinated against that disease. High vaccination rates make it difficult for the disease to spread because there are very few susceptible people in the population. Herd immunity is important for people who cannot be vaccinated (e.g. the very young, people with immune system disorders, or people who are very sick, such as cancer patients).

High herd immunity: Most of the population is immunised. The spread of the disease is limited. Only a few people are susceptible and become infected.

Low herd immunity: Only a small proportion of the population is immunised. The disease spreads more readily through the population infecting many more people.





DID YOU KNOW?

The level of vaccination coverage to obtain herd immunity differs for each disease. Highly contagious diseases (e.g. measles) need a much higher vaccine uptake (95%) than a less contagious disease such as polio (80-85%).

2. Attenuated viruses provide long term immunity to their recipients and generally do not require booster shots. Why do you think attenuated viruses provide such effective long-term immunity when inactivated viruses do not?

____

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____

____

3. (a) What is herd immunity? ____

____

____

(b) Why are health authorities concerned when the vaccination rates for an infectious disease fall? _______________

____

____

4. Some members of the population are unable to be vaccinated. Give an example and explain why herd immunity is very important to them?

____

____

____

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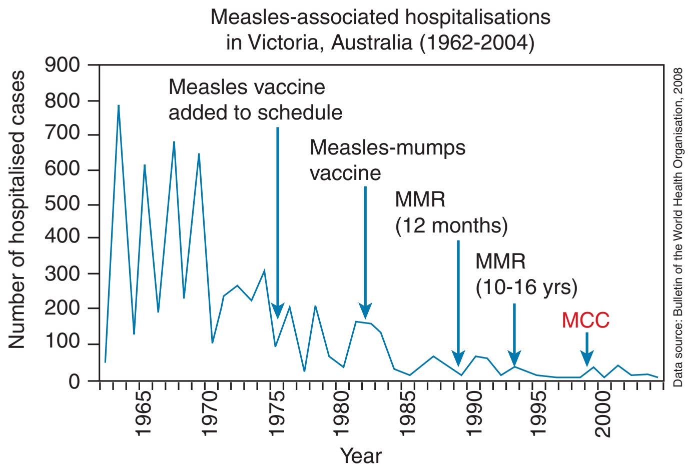
187 Vaccines Can Eliminate Infectious Disease

Key Idea: Vaccination programmes have been successful in the global eradication of smallpox, but other diseases (such as influenza) are more difficult to eradicate.

To date, the only infectious disease globally eradicated has been smallpox. Several factors lead to this success. Smallpox is easily identifiable by its characteristic rash making surveillance and containment of infected patients easier. It has no other natural carriers so once immunisation rates reached a critical level, its spread through the population was limited. Other diseases can be more difficult to eradicate. This is especially true for diseases that have a long period between infection and the symptoms showing (e.g. TB) or diseases caused by pathogens with high rates of mutation (e.g. *influenzavirus* or HIV).

Measles elimination in Australia

Measles is a highly contagious disease, one infected person can infect 12-18 people during their infectious period. In 2014, the World Health Organisation (WHO) announced measles had been eliminated from Australia. High vaccination rates contributed to its elimination. However, measles still occurs in other countries so it could be reintroduced if an infected traveller entered Australia. Maintaining high levels of vaccination is important in preventing its reintroduction.



The graph above shows the role of vaccination in reducing measles hospitalisations in the state of Victoria.
MMR is the introduction of the measles/mumps/rubella vaccine.
MCC (measles control campaign) was an extensive mass vaccination and monitoring campaign.

Whooping cough (above) is a respiratory disease caused by the bacterium *Bordetella pertussis*. Despite high vaccination rates, whooping cough is increasing in Australia. Several factors may be contributing to this.

- Until 1997, a whole vaccine was used. It contained hundreds of different antigens and provided protection against many strains of the pertussis pathogen. In 1999, an acellular vaccine, which does not contain the whole pathogen, was introduced (inset above). It only contains five antigens and so provides less protection.
- New strains of *B. pertussis* are evolving, and the new vaccine is not effective against them.
- More adults who were vaccinated against whooping cough in childhood are contracting the disease. This suggests the effectiveness of the vaccine declines over time.

1. The graph above provides long term immunity data for measles in Victoria. Use this data to provide evidence for the role of vaccination programmes in eliminating measles from Australia:

2. What could happen if vaccination rates for measles fell too low?

3. (a) Why could the change to a new vaccine have affected the rates of whooping cough in Australia:

   (b) Why do you think a new vaccine was introduced?

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188 KEY TERMS AND IDEAS: Did You Get It?

1. Contrast the innate and the adaptive immune responses with reference to the basic action and the cells involved:

2. The photograph on the right shows the effect of a pathogen infecting a human.

(a) Name the defensive response occurring:

(b) What is happening to the blood vessels at this location?

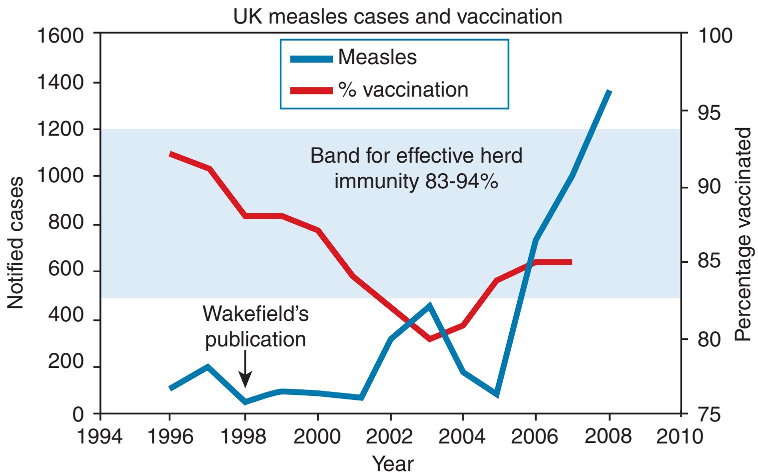
(c) Name the substance responsible for the change in the blood vessels:

(d) What type of cell is the substance released from?

(e) During this response, the number of white blood cells increases/decreases (delete one).

(f) The process occurring here is an example of innate immunity / adaptive immunity (delete one).

3. In 1998, Dr Andrew Wakefield and his colleagues published a paper linking the measles, mumps, and rubella vaccine (MMR) to an increase in autism rates. As a result, the uptake of the MMR vaccine in the UK dropped, and several measles outbreaks occurred. **Dr Wakefield's paper has since been retracted by the journal in which it was published as it was found to be fraudulent and flawed in several aspects, e.g. sample size of only 12, with no control group.** Since the publication of Wakefield's paper, 20 large scale epidemiologic studies into MMR and autism have been carried out in several countries. All have shown that **the MMR vaccine does not cause autism**. However, the damage has been done, and health authorities must now convince the public that the vaccine is safe.



The graph above shows the number of measles cases in the UK, together with percentage vaccination, 1994-2008.

(a) What happened to MMR vaccination rates after the publication of Wakefield's study?

(b) What is the trend in measles cases in the UK since 2006?

(c) Give a likely explanation for this trend:

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SHE

UNIT 2
Topic 2

Transmission and Spread of Disease

Key terms

endemic disease
epidemic
epidemiology
hygiene
immunised
isolation
outbreak
pandemic
prevalence
quarantine
susceptible
vaccination programme

Activity number

The transmission of disease

Key skills and knowledge

- ☐ 1 Recall the modes of disease transmission. Recognise that the transmission of disease is aided by the regional and global movement or organisms and describe examples to illustrate this. — 172 189
- ☐ 2 Identify and explain the interrelated factors affecting immunity, including the persistence of pathogens within the host, the proportion of the population that is immune or immunised (vs susceptible), and the mobility of individuals in the affected population. — 189 190 195
- ☐ 3 Analyse these factors to predict potential outbreaks of disease. — 189 190



CDC

Spread of disease and epidemiology

Key skills and knowledge

- ☐ 4 Evaluate strategies to control the spread of disease, including: — 191
  - personal hygiene measures
  - community level controls such as contact tracing, quarantine, travel restrictions, restrictions on mass gatherings, and school and workplace closures.
- ☐ 5 **SHE** Discuss the role of quarantine in protecting Australia's agriculture, industry, and environment from disease. — 192
- ☐ 6 Critically analyse relevant and current information to make decisions and justify them in regard to best practice for the prevention of disease outbreaks. — 192 193 198
- ☐ 7 Use secondary data or computer simulations to interpret models of the spread of disease. — 194
- ☐ 8 **PRAC** Investigate the effectiveness of hand washing compared to alcohol-based gels in reducing the bacterial load on hands. — 193
- ☐ 9 **SHE** Explain how mass vaccination programmes are more successful when informed by disease outbreak models. — 189
- ☐ 10 **SHE** Discuss factors contributing to the susceptibility of populations in Asia to disease outbreaks. — 196

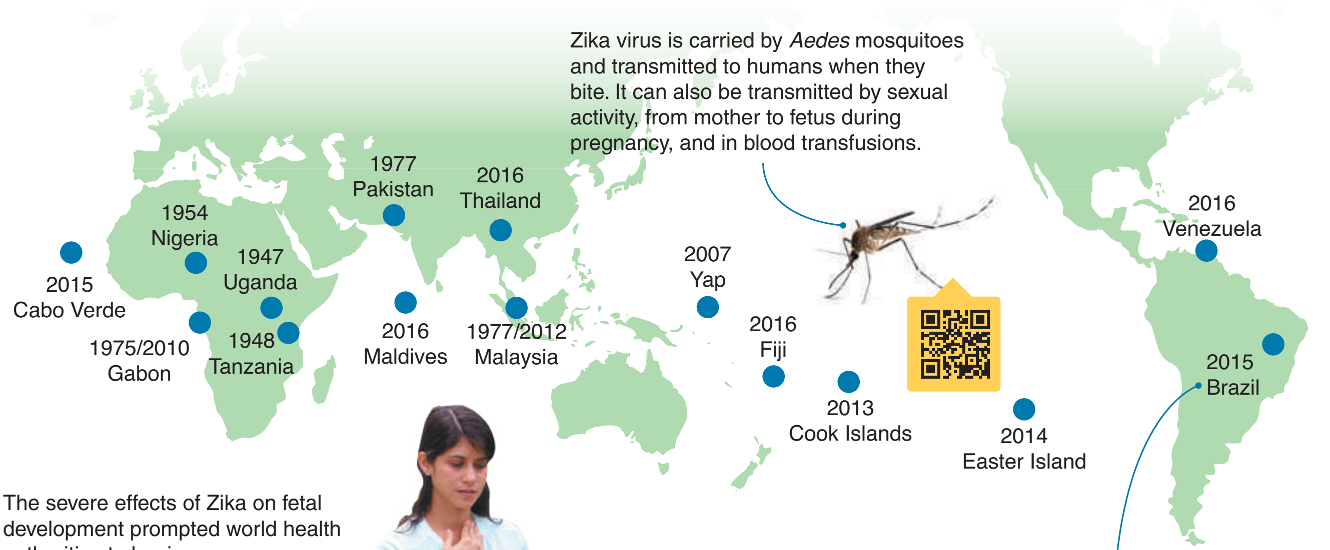
189 Patterns of Disease

Key Idea: Studying the prevalence and spread of a disease gives insights into its origins and how to combat it.

Diseases present at constant low levels in a population or region are known as **endemic** diseases. Occasionally there may be a sudden increase in the **prevalence** of a particular disease. On a local level this is known as an **outbreak**. When an infectious disease spreads rapidly through a nation and affects large numbers of people it is called an **epidemic**. On rare occasions a new kind of disease will appear and spread to other countries. The rapid spread of a disease throughout the world is a **pandemic**. Examples of pandemic diseases include HIV/AIDS, influenza, and Zika virus.

Zika virus: An example of global disease spread and its containment

Zika virus was first isolated from the area of the Zika Forest in Uganda in 1947. Since then it has spread slowly across the globe with outbreaks in the Americas in 2015 and 2016. Zika causes a mild fever and rash that is not usually serious in adults. However, in the last few years, infection of pregnant women by Zika has been linked to, microcephaly (small head and brain) in their newborns.



Zika virus is carried by *Aedes* mosquitoes and transmitted to humans when they bite. It can also be transmitted by sexual activity, from mother to fetus during pregnancy, and in blood transfusions.

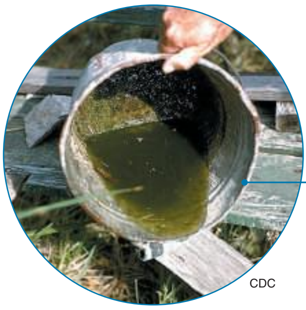
Zika virus became an important international concern in 2015 and 2016 in the lead up to and during the 2016 Rio Olympics. Concerns focussed on the movement of spectators, tourists, and athletes and the spread of the disease around the globe as they returned home after the events.

The severe effects of Zika on fetal development prompted world health authorities to begin an awareness campaign to limit Zika's spread and reduce the risk of contracting it. The campaign focussed on prevention, including travel advisories in unaffected countries and awareness campaigns in affected countries.

CDC

Insect repellent should especially be used if wearing clothing that exposes the skin.

People are advised to wear long sleeves and pants to prevent mosquito bites.



CDC

Reducing areas where water can stagnate reduces mosquito breeding sites.

1. (a) Which general direction has Zika virus spread across the globe? ______________________

   (b) Describe the area that Zika virus appears to be generally confined to and explain this: ______________________

   ____

2. How is Zika virus transmitted? ______________________

   ____

3. Describe how the spread of Zika virus can be reduced: ______________________

   ____

   ____

   ____

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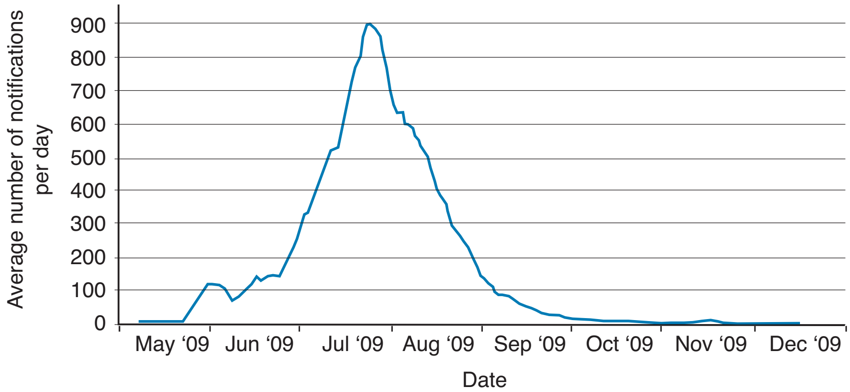
H1N1/09 pandemic

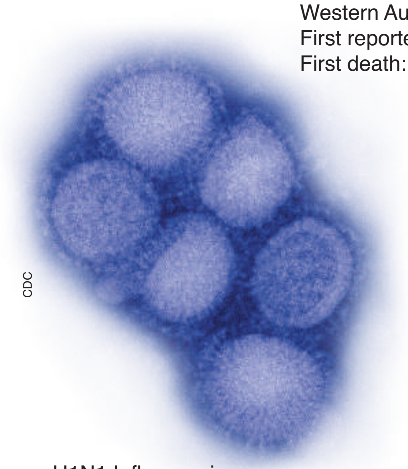
In 2009, the H1N1/09 subtype of the influenza virus (formerly known as swine flu), crossed the species barrier to humans in Mexico and from there spread to the rest of the world. Cases in Australia were first reported in May 2009 and quickly rose to a peak in late July. Total cases for 2009 were over 37,000. The 2009 H1N1/09 pandemic was the first influenza pandemic of the 21st century. The strain is now included in the annual flu vaccination.

Epidemiologists gather data on the number of infected people (**morbidity**) and the number of people that have died (**mortality**) within a population. These data help to establish the **incidence** (number of new cases per unit time) and **prevalence** (number of infected people expressed as a proportion of the population) of the disease in the population at any given time. **Aetiology** is the study of the cause of a disease. It can assist in pinpointing the origin of new diseases, such as the H1N1/09 influenza virus (swine flu).

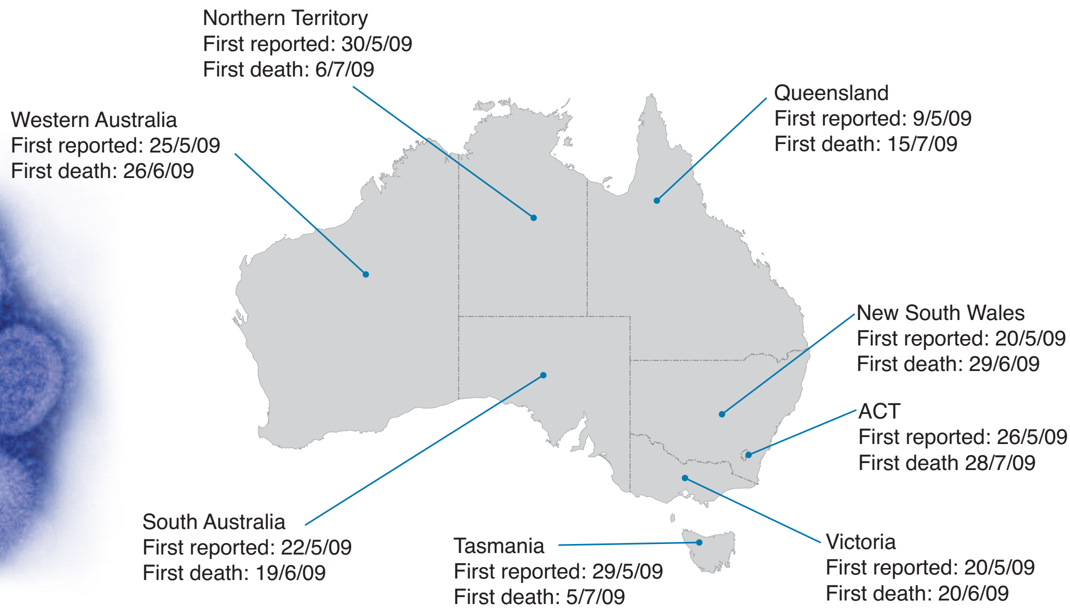
Australian H1N1/09 flu cases 2009



Spread of H1N1/09 flu across Australia



H1N1 Influenzavirus



4. In which Australian state was H1N1/09 first reported? ______________________________

5. (a) Why was H1N1/09 classed as a pandemic? ______________________________

____

(b) What was the most likely origin of H1N1/09 spread in Australia? Explain your answer: ______________________________

____

____

(c) Suggest likely reasons for the rapid fall-off in the incidence of H1N1/09 in Australia after August 2009:

____

____

6. Why is it important to establish the incidence of a disease when it begins to spread through a community?

____

____

____

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190 Predicting Future Patterns of Disease

Key Idea: Predicting future disease outbreaks relies on monitoring current disease episodes and using population statistics to identify potentially vulnerable groups of people.

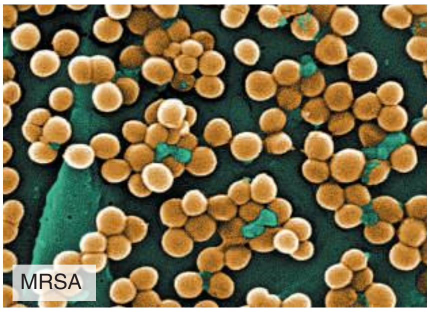
Disease outbreaks have occurred throughout history. The plague that spread through Europe in the 1400s (the Black Death) and again in the mid 1600s (the Great Plague) were some of the most devastating outbreaks ever. The Spanish flu was the last great worldwide pandemic. Although various pandemics have occurred since, improved global cooperation and more effective action by health authorities have improved disease containment and most pandemics rarely last longer than a few months.

Predicting future disease is often a case of identifying diseases in animals that could cross over to humans. Many infectious diseases have an animal origin including various strains of influenza (e.g. avian flu H5N1 and swine flu H1N1). Identifying these pathogens in animals, especially livestock and poultry living in close proximity to humans, can help prepare for possible outbreaks.

Population density is important to how quickly an infectious disease can spread. Cities generally have very high population densities, with some reaching densities of over 20,000 per km^2. Disease spreads most quickly in areas with poor living conditions, poor sanitation, and low levels of immunity. For example, the Spanish flu initially spread quickly due to the cramped confines of military camps and hospital wards.

How quickly an infectious disease spreads also depends of the population's mobility. The 1918 Spanish flu spread around the world due to infected troops returning home and taking the disease with them. Part of predicting where and when diseases will occur is being able to predict the movements of groups of people. For example people moving from rural areas to cities may transport potential pathogens from livestock.

The spread of disease also depends on the mode of transmission. Is it spread by air borne particles or by touch? The most feared scenario is an airborne pathogen that is highly contagious, has a long infectious period, and is ultimately deadly.



Resistance to antibiotics is becoming a greater problem with many bacterial strains becoming extremely difficult to treat. Plans need to be in place for if (or when?) a highly resistant pathogenic bacteria begins to spread through the general population.

Possible climate change is already being taken into account to predict where possible outbreaks may occur. For example, malaria made spread further north and south from the tropics as the climate becomes more favourable for its mosquito vectors.

1. Explain how each of the following are important in predicting where the next epidemic may originate:

(a) Pathogen in livestock related to human diseases: ______________________

____

(b) Population density: ______________________

____

(c) Global travel networks: ______________________

____

(d) Resistance to antibiotics: ______________________

____

(e) Climate change: ______________________

____

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Seasonal patterns

Some diseases are seasonal, showing patterns of increased or decreased prevalence at specific times of the year. Influenza (the flu) commonly becomes more prevalent in the winter of both the Southern and Northern Hemispheres. Ross River fever becomes more common during the summer/autumn rainy season (January to March). The seasonal patterns of these diseases allow for simple predictions of when most cases will occur. For example, health authorities prepare for increased influenza cases in winter by offering the latest vaccines.

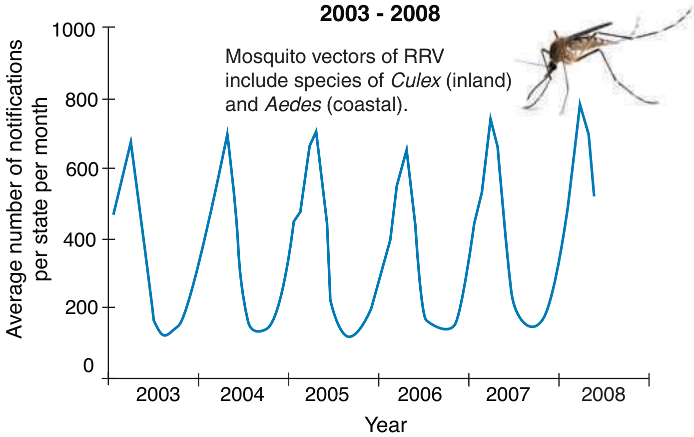
Ross River virus

Ross River virus (RRV) is endemic to Australia, Papua New Guinea, and several other islands of the South Pacific and causes Ross River fever. RRV is transmitted by mosquitoes and may have natural reservoirs in native Australian mammals. In Australia, most RRV infections occur in the wetter tropical areas of QLD, WA, and NT. There have been several large outbreaks since the first noted outbreak in 1928. The largest outbreak occurred in 1979-80 across the Western Pacific, affecting 60,000 people.

Ross River fever

Symptoms of Ross River fever include fever, rash, and arthritic-like symptoms causing extreme pain in various joints. In most cases, the disease lasts about a month but can reoccur over a period of years. Currently a blood test is the only way to confirm Ross River fever and there is no vaccine.

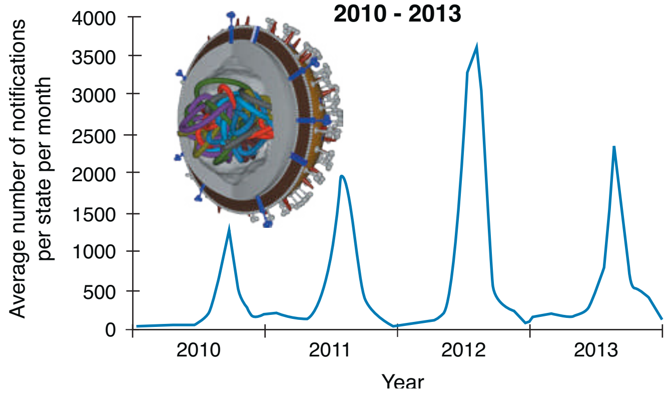
Notifications of Ross River virus in Australia, 2003 - 2008



Influenza

Although it is often looked upon as simply a bad cold, influenza (commonly called "the flu") has arguably caused more human deaths than any other disease throughout history. Influenza occurs in seasonal epidemics, usually infecting around five million people globally, and causing the death of between 250,000 and 500,000 people annually. The influenza virus continually changes in two ways. **Antigenic drift** involves small cumulative genetic changes over time. Occasionally the virus will also undergo **antigenic shift**, producing an entirely new strain that causes a pandemic. The latest of these is the H1N1/09 strain, commonly referred to as swine flu. This strain caused around 14,000 deaths globally. Compare this the Spanish flu pandemic of 1918-1920, during which possibly up to 100 million people died globally (more than all deaths during World War I and possibly as many as World War II).

Notifications of Influenza in Australia 2010 - 2013



4. (a) How is the Ross River virus transmitted to people? ______

   (b) Suggest why cases of Ross River fever are more prevalent in January to March: ______

   (c) There was a large mosquito outbreak in 2013 in Newcastle NSW. Predict the effect of this on the prevalence of Ross River fever:

   ______

5. (a) What time of the year is the influenza virus most prevalent? ______

   (b) Why must people receive the flu vaccine every year if they want to remain protected against influenza?

   ______

6. Why is it useful to track the incidence of diseases such as Ross River fever and influenza? ______

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191 Containing the Spread of Disease

Key Idea: Preventing the entry and spread of pathogens is important in protecting a country's population and industries from infectious diseases.

Many factors can influence the spread of disease, including the social climate, diet, general health, and access to medical care. Human intervention and modification of behaviour, including vaccination, can reduce the transmission rate of some diseases and inhibit their spread. Global air travel and international trade in commodities has increased the risk that diseases of humans, livestock, and crops will be spread between countries. Australia is fortunate in that its geographical isolation has helped to prevent the spread of disease from other parts of the world.

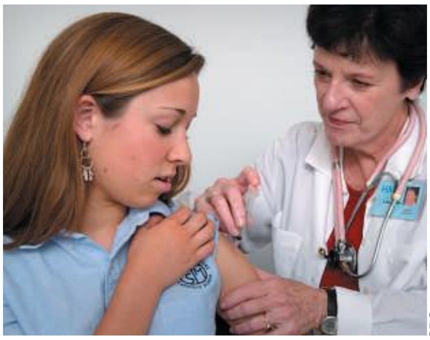
Transmission of disease can be reduced by adopting 'safe' behaviours. Examples include using condoms to reduce the spread of STIs, **isolation** of people already infected, or establishing quarantine procedures for people who have been exposed to infection.

The environment can be made less suitable for the growth and transmission of pathogens. For example, spraying drainage ditches and draining swamps eliminates breeding habitats for mosquitoes carrying diseases such as Zika virus and malaria.

Disinfectants and sterilisation techniques, e.g. autoclaving (above), destroy pathogenic microbes before they have the opportunity to infect. The use of these techniques in medicine has significantly reduced post operative infections and associated deaths.

The development of effective sanitation, sewage treatment, and treatment of drinking water has virtually eliminated dangerous waterborne diseases from developed countries. These practices disrupt the normal infection cycle of pathogens such as cholera and giardia.

Appropriate personal hygiene practices reduce the risk of infection and transmission. Soap may not destroy the pathogens but washing will dilute and remove them from the skin. Although popular, antibacterial soaps encourage the development of strains resistant to antimicrobial drugs.



CDC

Vaccination schedules form part of public health programmes. Vaccination is one of the most effective ways of preventing transmission of contagious diseases. If most of the population is immunised, herd immunity limits outbreaks to sporadic cases and prevents epidemics.

1. (a) Identify three ways in which the environment can be made less suitable for establishment and transmission of diseases:

(b) How is disease transmission reduced in medical care situations?

(c) Why is sanitation important in preventing the spread of disease?

2. Why is reducing the prevalence of disease preferable to trying to contain an outbreak?

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192 Quarantine and Biosecurity

Key Idea: Quarantine is a way of ensuring diseases do not enter a new area. It is an important part of a biosecurity programme.

Biosecurity is important for Australia which, because of its relative isolation, has managed to exclude many of the pathogens that infect plants and animals in other countries. Precautions such as **quarantine**, which isolates exposed individuals that may be infected, as well as screening of imported produce and international travellers, help to limit the entry of diseases into Australia. Quarantine is distinct from **isolation**, which aims to contain disease by isolating an already infected person.

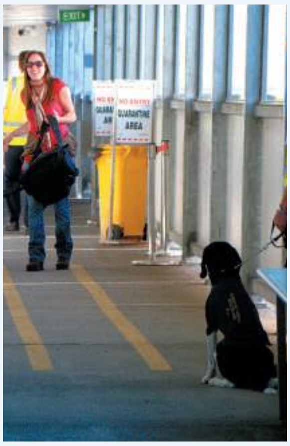
Biosecurity in Australia

Australia has strict biosecurity rules and measures in place to prevent the entry of pests and diseases into the country. For most people, this is most visible in airports when entering Australia from overseas. Passengers disembarking from aircraft are repeatedly reminded of what can and can't be brought into the country. Large fines can be instantly given to people who ignore the warnings. Inspection officers commonly use X-ray machines and detector dogs to check passengers' luggage for prohibited goods, especially fresh food or animal and plant materials.

Biosecurity inspections are also made on goods entering on cargo ships. Shipping containers are inspected for unwanted plants or animals that may have got into the container when loading. This is common in fresh food containers (e.g. fruits). If pests are found, the containers may be turned away. Inspection of many goods occurs at the home port before they are loaded on to cargo ships.

Goods PROHIBITED entry into Australia without authorisation

- Milk and dairy products
- Seeds and beans
- Popping corn and raw nuts
- Eggs and egg products
- Fresh fruit and vegetables
- Live animals
- Meat and fish products
- Live plants
- Biological materials (e.g. human/animal vaccines)
- Deer horn/velvet
- Soil and sand



Bjørn Christian Torrissen CC3.0

The role of quarantine

When organisms are brought into Australia they must undergo a quarantine period to monitor health and ensure no pests or diseases are in or on the organism. Quarantine may also apply to travellers who have been in contact with infected persons or have returned from places known to have disease outbreaks. These quarantine procedures were used during the SARS epidemic in 2003 and the swine flu pandemic in 2009.

The equine industry is an important part of the Australian economy. Live horses brought into the country are quarantined to check for diseases that may affect the industry. In August 2007, equine influenza was discovered in horses at the Eastern Creek Quarantine Station, the first time it had entered Australia. Somehow, it escaped quarantine, possibly through human error, and spread throughout NSW, reaching as far as Gatton and Warwick in Queensland. Due to strict non-movement orders, the outbreak was contained by February 2008.

Equine influenza is highly infectious and so easily spread.

1. Why is biosecurity important for Australia? ______________________________

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2. Why is pre-inspecting goods at the home port a useful biosecurity measure? ______________________________

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3. How does quarantine prevent the spread of disease? ______________________________

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4. How does Australia's geographic position help prevent the entry and spread of disease in Australia? ______________________________

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SHE

ISBN: 978-1-927309-83-4

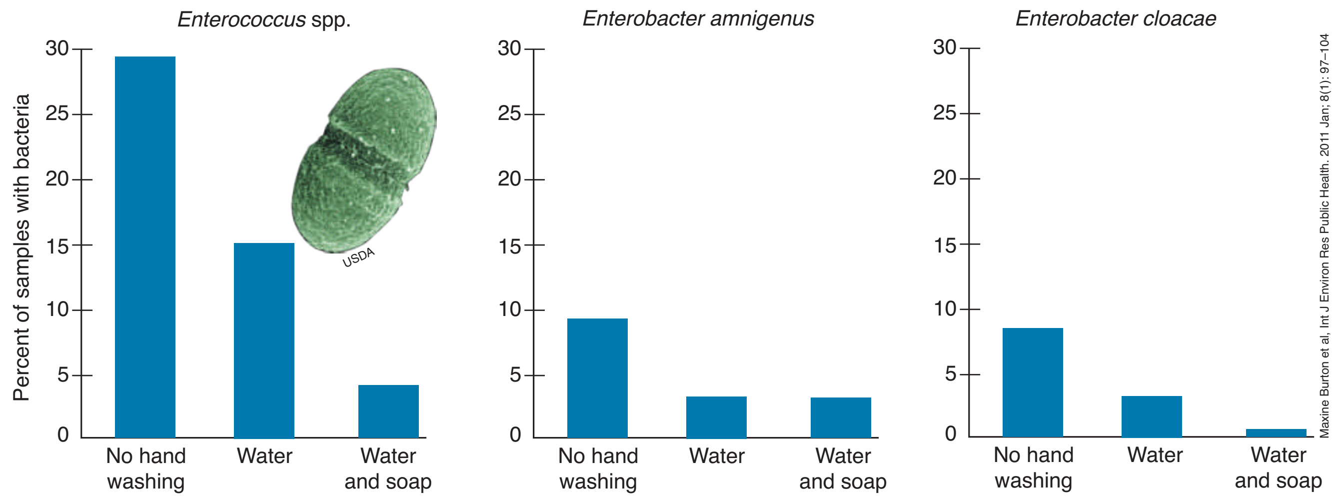
193 The Effectiveness of Hand Washing

Key Idea: Hand washing is an important and simple method to prevent the spread of disease, but must be properly done.

We as humans spend much of our time manipulating objects with our hands, so it follows that our hands are covered with the microorganisms found in our environment. These microbes can then be easily transferred by touch to our mouths, such as when eating, or to other people, such as when handing them an object. Hand washing after contact with potentially contaminated material reduces the chance of transmitting microbes to our internal environment or to others.

Testing the effectiveness of hand washing

- A 2011 study performed the following experiment on the effectiveness of hand washing.
- Twenty volunteers deliberately contaminated their hands by contact with hard surfaces such as hand rails and door knobs in public areas.
- They were then randomly allocated to one of three groups: no hand washing, hand washing with tap water, or handwashing with soap and tap water. No instructions were given as to how to hand wash or for what length of time. Volunteers simply washed their hands as they would normally.
- Swabs were then taken from the volunteers' hands and transferred to agar plates. These were incubated at 35°C for 48 hours. This procedure was carried out 24 times for each volunteer for a total of 480 samples.
- The results are shown below. The bacteria found all occur in the intestines of animals (collectively called faecal coliforms).



1. (a) Was hand washing an effective way to remove bacteria from the hands? ______________________

   (b) Which was the most effective method of removing bacteria from the hands? ______________________

2. Which bacterium was most common on the hands? ______________________

3. Why do you think the researchers gave no handwashing instructions to the volunteers? ______________________

4. Design an experiment that would investigate the difference between washing hands with soap and using isopropyl alcohol (hand sanitiser) in removing microbes:

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194 Modelling Disease Outbreak and Spread

Key Idea: Being able to model the spread of a disease can help predict where, when, and how it will spread.

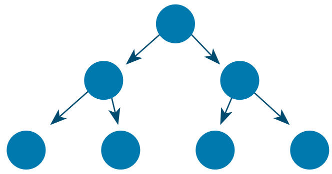
Modelling how a disease spreads can help preparation for an eventually outbreak. Factors in the model must take into account how infectious a pathogen is and for how long, the density and mobility of the population, and even the level of mortality of infected people. These models can be used to test the effectiveness of public health measures.

Modelling a disease

- A spreadsheet can be used to model the spread of disease. There are also numerous online models that can be used.
- In the most simple model whenever an infected people meets another a new infection occurs. The number of interactions at each infection cycle affects the spread of the disease.
- Using a spreadsheet, we will first model an infected person meeting (and infecting) two other people. In this model once the infected person has infected two people they are no longer infectious.
- Working in pairs, enter the following into a spreadsheet:

	A	B
1	New infections	Total Infections
2	1	=SUM($A$2:A2)
3	=A2*2	=SUM($A$2:A3)
4	=A3*2	=SUM($A$2:A4)
5	=A4*2	=SUM($A$2:A5)
6	=A5*2	=SUM($A$2:A6)
7	=A6*2	=SUM($A$2:A7)
8	=A7*2	=SUM($A$2:A8)

One infection cycle. Copy this down to row 12 (10 cycles of interactions).



A simple infection model. One person infects two, who infect two more...

1. How many new infections are there per infection cycle after 10 infection cycles? ____________________

2. How many infected people are there in total after 10 infection cycles? ____________________

- Now set the interactions per infected person to 3 (A2*3) and reset the model.

3. How many new infections are there per cycle of infection after 10 infection cycles? ____________________

4. How many infected people are there after 10 cycles of infection? ____________________

- We can now extended the model by adding in a little randomness. The number of people interacting with each infected person may not always be the same. In our extended model, we shall randomise the number of people interacting to between 1 and 4.

	A	B	
1	New infections	People interacted with per person	Total infected people
2	1	=RANDBETWEEN(1,4)	=SUM($A$2:A2)
3	=A2*B2	=RANDBETWEEN(1,4)	=SUM($A$2:A3)
4	=A3*B3	=RANDBETWEEN(1,4)	=SUM($A$2:A4)
5	=A4*B4	=RANDBETWEEN(1,4)	=SUM($A$2:A5)
6	=A5*B5	=RANDBETWEEN(1,4)	=SUM($A$2:A6)
7	=A6*B6	=RANDBETWEEN(1,4)	=SUM($A$2:A7)
8	=A7*B7	=RANDBETWEEN(1,4)	=SUM($A$2:A8)

5. Run the model five times by recalculating the spreadsheet using the **recalculate** or **calculate now** option (depending on your spreadsheet). On average, how many people in total have been infected after ten cycles?

____

- Not all interactions will result in an infection. The pathogen may not be highly infectious or the correct mode of transmission may not have occurred (for example a person with a cold may have been careful where and how they coughed).
- First we need to decide the probability of each interacting person being infected. For this model we will say there is a 50% chance that any interacting person will be infected. We shall first produce a random number between 0 and 1 (see * below). We can now use this block of infected (1) or not infected (0) cells in our model. Once the formula is set up, you can recalculate the spreadsheet to obtain different infection scenarios.

	A	B	C	D
1	New infections	People interacted with per person	Infected people	Total Infected people
2	1	=RANDBETWEEN(1,4)	=IF(B2=1,$B$15,IF(B2=2,$B$15+$B$16,IF(B2=3,$B$15+$B$16+$B$17,IF(B2=4,$B$15+$B$16+$B$17+$B$18))))	=SUM($A$2:A2)
3	=A2*C2	=RANDBETWEEN(1,4)	=IF(B3=1,$B$15,IF(B3=2,$B$15+$B$16,IF(B3=3,$B$15+$B$16+$B$17,IF(B3=4,$B$15+$B$16+$B$17+$B$18))))	=SUM($A$2:A3)
4	=A3*C3	=RANDBETWEEN(1,4)	=IF(B4=1,$B$15,IF(B4=2,$B$15+$B$16,IF(B4=3,$B$15+$B$16+$B$17,IF(B4=4,$B$15+$B$16+$B$17+$B$18))))	=SUM($A$2:A4)
5	=A4*C4	=RANDBETWEEN(1,4)	=IF(B5=1,$B$15,IF(B5=2,$B$15+$B$16,IF(B5=3,$B$15+$B$16+$B$17,IF(B5=4,$B$15+$B$16+$B$17+$B$18))))	=SUM($A$2:A5)
6	=A5*C5	=RANDBETWEEN(1,4)	=IF(B6=1,$B$15,IF(B6=2,$B$15+$B$16,IF(B6=3,$B$15+$B$16+$B$17,IF(B6=4,$B$15+$B$16+$B$17+$B$18))))	=SUM($A$2:A6)
7	=A6*C6	=RANDBETWEEN(1,4)	=IF(B7=1,$B$15,IF(B7=2,$B$15+$B$16,IF(B7=3,$B$15+$B$16+$B$17,IF(B7=4,$B$15+$B$16+$B$17+$B$18))))	=SUM($A$2:A7)
8	=A7*C7	=RANDBETWEEN(1,4)	=IF(B8=1,$B$15,IF(B8=2,$B$15+$B$16,IF(B8=3,$B$15+$B$16+$B$17,IF(B8=4,$B$15+$B$16+$B$17+$B$18))))	=SUM($A$2:A8)
9	=A8*C8	=RANDBETWEEN(1,4)	=IF(B9=1,$B$15,IF(B9=2,$B$15+$B$16,IF(B9=3,$B$15+$B$16+$B$17,IF(B9=4,$B$15+$B$16+$B$17+$B$18))))	=SUM($A$2:A9)
10	=A9*C9	=RANDBETWEEN(1,4)	=IF(B10=1,$B$15,IF(B10=2,$B$15+$B$16,IF(B10=3,$B$15+$B$16+$B$17,IF(B10=4,$B$15+$B$16+$B$17+$B$18))))	=SUM($A$2:A10)
11	=A10*C10	=RANDBETWEEN(1,4)	=IF(B11=1,$B$15,IF(B11=2,$B$15+$B$16,IF(B11=3,$B$15+$B$16+$B$17,IF(B11=4,$B$15+$B$16+$B$17+$B$18))))	=SUM($A$2:A11)
12	=A11*C11	=RANDBETWEEN(1,4)	=IF(B12=1,$B$15,IF(B12=2,$B$15+$B$16,IF(B12=3,$B$15+$B$16+$B$17,IF(B12=4,$B$15+$B$16+$B$17+$B$18))))	=SUM($A$2:A12)
13				
14				
15	= RAND()	=IF(A15>0.5,1,0)		
16	= RAND()	=IF(A16>0.5,1,0)		
17	= RAND()	=IF(A17>0.5,1,0)		
18	= RAND()	=IF(A18>0.5,1,0)		
19				
20				
21				

* Produces a 50% probability of infection

IF statement incorporates the number of interactions and the probability of infection into the model

6. Run the model five times by recalculating the spreadsheet as before. On average how many people in total have been infected after ten cycles now?

____

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7. The third model opposite is much more realistic than the first, but still lacks many factors that would affect the model outcome. List at least three factors that could be added to the model to make it even more realistic:

Mathematical models and vaccination

Mathematical models of the effect of vaccination on populations have been used since the mids 1700s. In 1760 Swiss mathematician Daniel Bernoulli published a study on the effect of immunisation with cowpox (against smallpox) on the life expectancy of the immunised population. Around the time of the First World War Ronald Ross produced mathematical models to show that malaria could be controlled without the need to remove every last mosquito. These mathematical models are the basis for many vaccination programmes and show why herd immunity is an important part of population immunity.

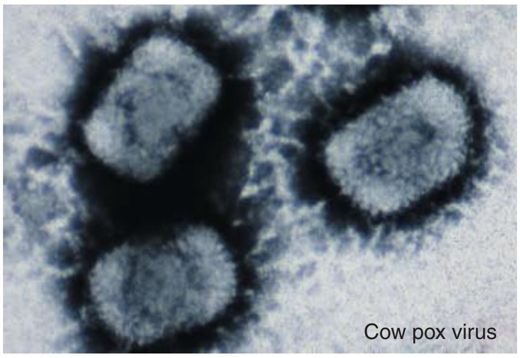
- All that is needed for the incidence of disease to decline is that on average every case or primary infection should generate less than one other case or secondary infections.
- The number of secondary infections caused by an infectious individual is denoted as R. $\mathbf{R_0}$, the basic reproductive number, is the number of secondary infections caused by a primary infection introduced into a wholly susceptible population.
- $\mathbf{R_{0p}}$, the basic reproductive number under vaccination, is the number of secondary infections caused by a primary infection introduced into a population where a proportion *p* of the population is vaccinated. For a perfect vaccination that confers life long immunity:

$$R_{0p} = (1 - p)\,R_0$$

- p_c is the critical vaccination proportion that will achieve eradication. To achieve this the basic reproductive number under vaccination (R_{0p}) must be just less than 1, so:

$$p_c = 1 - \frac{1}{R_0}$$

Calculating p_c requires estimates of R_0 (right)


Cow pox virus

Estimates of R_0 for populations and dates

Infection	Location	Date	R_0
Measles	Senegal	1964	18
Smallpox	West Africa	1960	2.3
Mumps	UK	1987	8
Rubella	USA	1967	6
Influenza	UK	2010	1.5

8. How are mathematical and computer models useful in controlling disease?

9. What is the critical vaccination proportion for each of the following diseases:

(a) Measles:

(b) Mumps:

(c) Influenza:

10. Why is the p_c of measles so high?

11. Ebola is a deadly disease. An outbreak in West Africa in 2014 killed around 11,000 people. However there is no vaccination programme for Ebola and outbreaks are normally controlled with simple sanitation measures such as hand washing and disinfection. Ebola has an R_0 of 2. How does this tell us that vaccination is not absolutely necessary to control this disease?

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195 Emerging Diseases

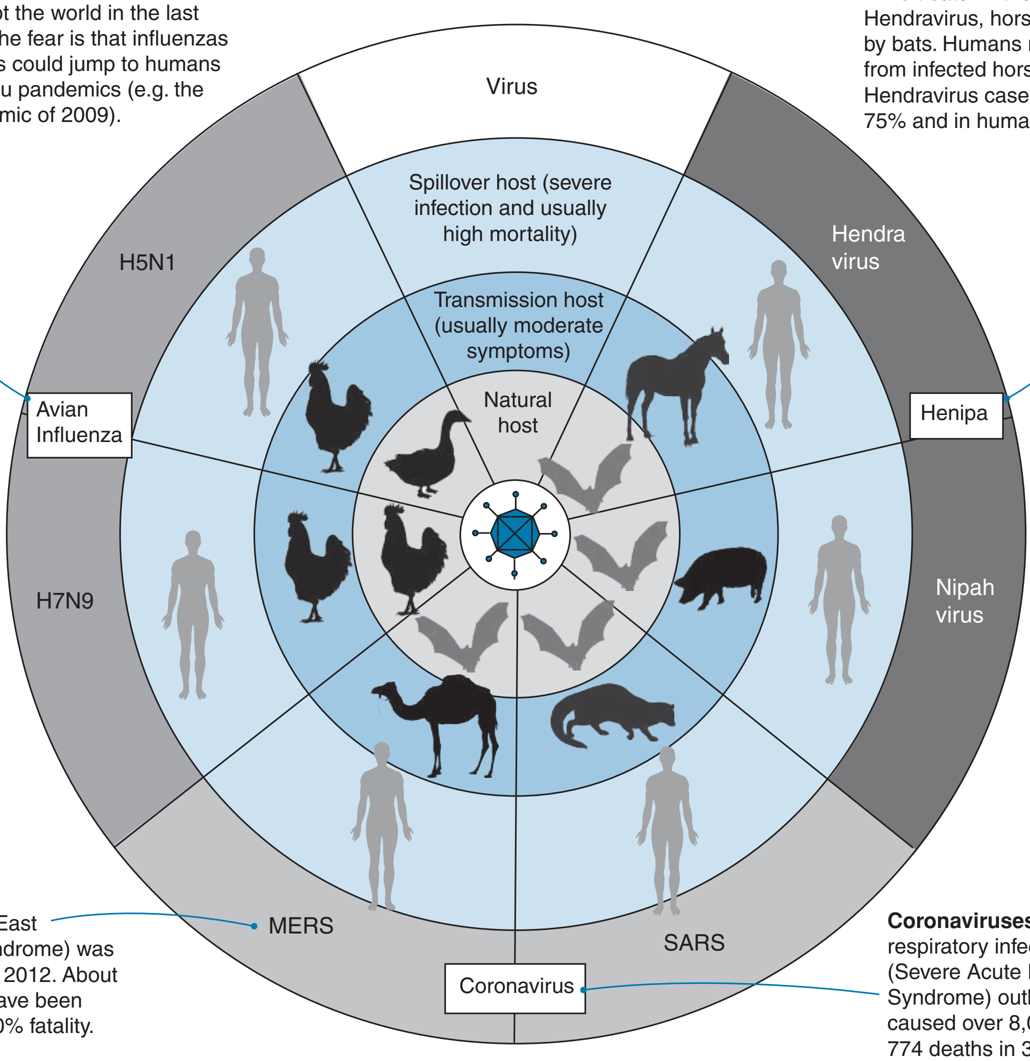
Key Idea: Emerging diseases are diseases that are new or have increased in incidence in the human population in recent times and as such pose a risk of rapidly spreading.

Emerging diseases are so named because they are new to humans or have increased markedly in incidence in recent times. Often, as with HIV/AIDS and avian influenza (H5N1), they are **zoonoses** (animal diseases that cross to humans). Zoonoses are capable of causing highly lethal pandemics (world-wide epidemics) amongst an unprepared population. The increasing incidence of multiple drug resistance in pathogens (including those that cause tuberculosis and malaria) has lead to the re-emergence of diseases that were previously thought to be largely under control. In the 1940s, many common but lethal bacterial diseases (e.g. diphtheria) were conquered using antibiotics. It is now evident that antibiotics are losing efficacy and must be used wisely to reduce the risk of resistance in the target populations. The global spread of viral diseases is controlled most effectively by immunising susceptible populations against circulating strains (as occurs with seasonal flu). The challenge for the control of viral disease is in the continual development of effective vaccines against newly emerging strains.

Many emerging diseases originate in animals and cross to humans (zoonoses). As humans put more pressure on wild spaces they come into contact with animal populations that may be the **reservoirs** (long-term natural hosts) of diseases new to humans. Some of these diseases are capable of not only crossing the species barrier to humans, but also being transmitted between humans.

Influenza is a common virus. However variations of this virus originating from birds have swept the world in the last few decades. The fear is that influenzas in birds and pigs could jump to humans causing major flu pandemics (e.g. the swine flu pandemic of 2009).

Henipaviruses are found naturally in fruit bats. In the case of Hendravirus, horses are infected by bats. Humans may be infected from infected horses. Fatality of Hendravirus cases in horses is 75% and in humans 60%.



MERS (Middle East Respiratory Syndrome) was first recorded in 2012. About a 1000 cases have been reported with 40% fatality.

Coronaviruses cause respiratory infections. The SARS (Severe Acute Respiratory Syndrome) outbreak in 2003 caused over 8,000 cases and 774 deaths in 34 countries.

1. (a) Where do many emerging diseases come from? ____________________

   (b) Suggest why diseases of this origin are becoming more prevalent: ____________________

   ____

2. Why are new diseases that can be transmitted between humans of such global significance? ____________________

   ____

   ____

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196 Managing Pandemics in the Asia Region

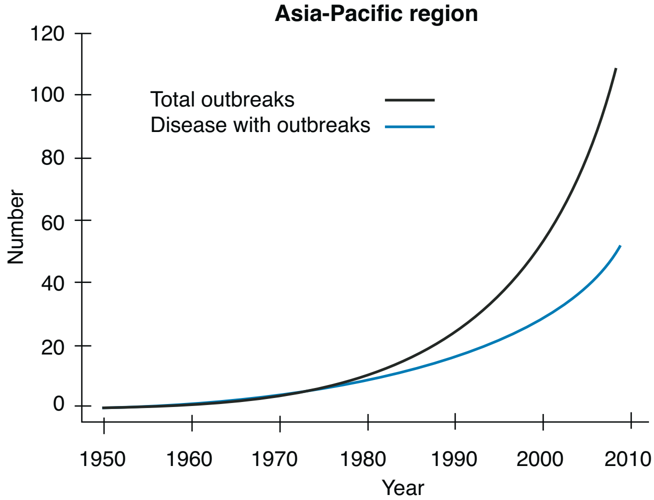
Key Idea: High population densities and various socioeconomic factors put Asia at risk of possible pandemics. The Asian region encompasses about 30% of the Earth's land area and 60% of the human population. With a vast range of countries, environments, beliefs, and political systems, producing a single actionable plan in the case of a pandemic is a difficult task in Asia. Most of the world's largest and most densely populated cities are found in Asia, making it particularly vulnerable to epidemics.

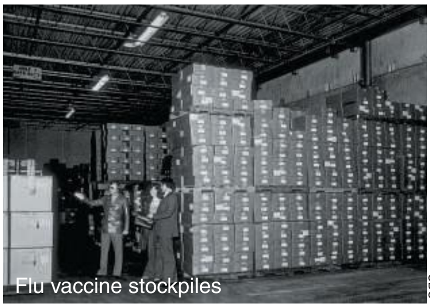
The total number of diseases with outbreaks and the total number of outbreaks has increased rapidly in the Asia-Pacific region since the 1950s (right).

The outbreak of SARS (Severe Acute Respiratory Syndrome) in 2003 showed that the public health systems and cooperation of nations throughout Asia needed strengthening. SARS appeared in China in November 2002, but Chinese officials did not inform the World Health Organisation (WHO) until February 2003. This lack of coordination resulted in SARS spreading much further and infecting many more people than it might have otherwise.

Since then, several other epidemics have swept through Asia, including the avian flu H5N1, of which the first human-human transmission was recorded in 2006. Since then, millions of domestic poultry have been culled in order to control the disease. A new subtype H7N9 was reported in 2013 in China.

Disease with outbreaks in the Asia-Pacific region




Flu vaccine stockpiles

CDC

The cost of vaccines and health care, especially in poorer countries, is a major barrier to preventing outbreaks. A key part of containing outbreaks is to ensure developing countries have access to vaccines and treatments. But it is not reasonable to expect a nation with a low GDP to spend a large percentage of its income on medical equipment it might not need.


CDC

A lack of health infrastructure is another barrier to the prevention of outbreaks. For example, India spends just 3% of its GDP on health care whereas Australia spends more than 10% of its GDP of health care. This can mean that if a disease outbreak does occur in a vulnerable country, health care services may not be able to meet the demand for resources and treatments.


Panic buying is common in uncertain times

Danny Cho CC 2.0

Managing information is an important part of any pandemic management plan. People can now get up-to-date information on a disease from the internet. It is important for health authorities to maintain communication with the public. This can help to avoid speculation and panic, which may result in people taking inappropriate and ineffective actions.

1. Why is the Asia region particularly vulnerable to epidemics and pandemics? ______________________

2. Why is maintaining communication with the public so important during a pandemic? ______________________

3. In small groups, discuss how countries in the Asia region collectively can prepare for a pandemic. Summarise your discussion as bullet points below.

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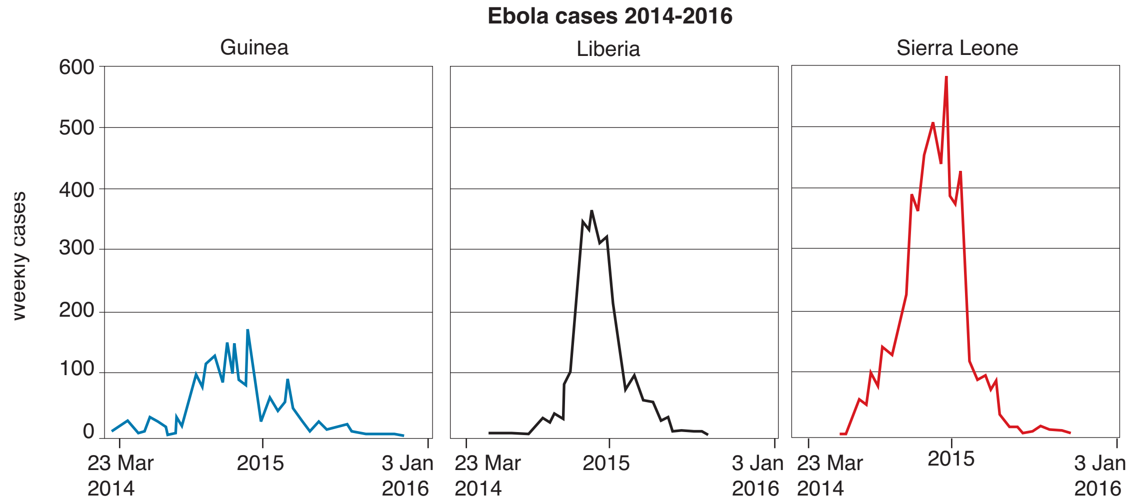
197 KEY TERMS AND IDEAS: Did You Get It?

1. Match each term to its definition, as identified by its preceding letter code.

Term		Definition
endemic	**A**	A branch of medicine that deals with the incidence, distribution, and control of disease.
epidemic	**B**	The occurrence of a disease on an international scale.
epidemiology	**C**	A disease or condition that is naturally present in a particular region or population.
incidence	**D**	The sudden occurrence of a large number of disease cases in a particular place.
outbreak	**E**	A period or place of isolation in which an individual who may have been exposed to a disease is placed in order to prevent them from possibly spreading a disease.
pandemic	**F**	The widespread occurrence of a disease within a community or population.
quarantine	**G**	The rate of occurrence or frequency of a disease in a population.

2. Study the graphs of the 2014-2015 West Africa Ebola outbreak below:



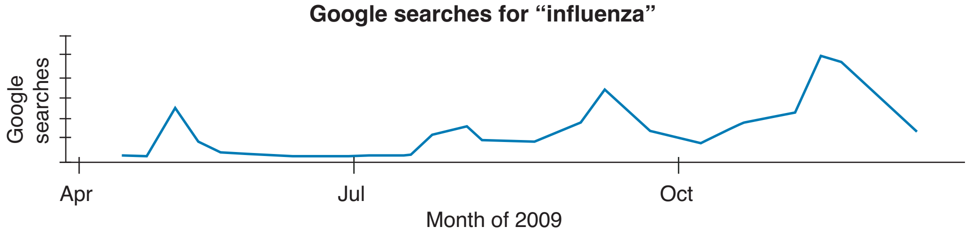
(a) In which country did Ebola first appear? ______________________________

(b) Which country had the greatest number of cases of Ebola? ______________________________

(c) What was the highest number of new cases reported per week? ______________________________

(d) When and where did this occur? ______________________________

3. Various health intelligence networks e.g. the Global Public Health Intelligence Network, monitor internet searches in order to determine if a disease outbreak is imminent. For example the graph below shows the number of Google searches including the word "influenza" for 2009:



How would monitoring the number of internet searches about diseases or symptoms help identify and locate potential outbreaks?

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198 Synoptic Question Unit 2, Topic 2

1. Over their lifetime, a person can develop resistance to specific pathogens. This is called acquired immunity. Acquired immunity can be obtained through natural or artificial means, and by active or passive processes.

   - Use examples to describe the differences between natural and artificially acquired immunity.
   - Discuss the differences and similarities between passive immunity and active immunity.

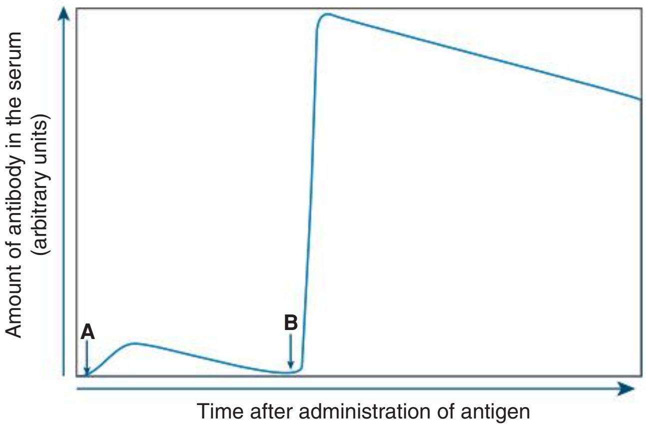
2. The graph right shows a primary and secondary immune response to an artificially introduced antigen.

   (a) What type of immunity is this?

   (b) What has occurred at point A?

   (c) What has occurred at point B?

   (d) Describe and explain the differences in the amount of antibody detected after each of the two events:



3. Pertussis, commonly known as whooping cough, is a highly contagious respiratory infection caused by the bacterium *Bordetella pertussis*. In Australia, the vaccine is given at two, four and six months of age. Booster doses are given at 18 months, four years and between 10-15 years. Epidemics occur in Australia every 3-4 years, but between 2008-2012 there has been a significant increase in cases of whooping cough. Most of the people contacting whooping cough have been adults who had been immunised in childhood.

   (a) Suggest why many adults are contracting whooping cough (even though they were vaccinated as children):

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(b) What effect could the high number of whooping cough cases have on young children who have not yet completed their vaccination schedule?

(c) How could the rates of whooping cough be reduced in Australia?

4. It is important to maintain high standards of hygiene in medical environments (e.g. hospitals or aged care facilities) to prevent the spread of pathogens. Handwashing with soap and water reduces the number of bacteria present, but it is not always convenient or possible to do this. The use of alcohol-based sanitisers has become a common alternative.
The data right shows the effect of handwashing or alcohol sanitiser on reducing bacterial load on the fingers of a group of intensive care nurses. 204 samples were taken from the nurses' fingers to determine the base level of contamination (shown by growth of bacterial colonies on agar). The nurses were then split into two groups (soap or alcohol rub). After they had cleaned and dried their hands, the fingers were pressed onto agar to determine the remaining bacterial load.

The effect of hand wash versus alcoholic hand rub on the disinfection of hands.

Bacterial growth on agar plates	Untreated hands (*n* = 204)	After soap & water wash (*n* =102)	After alcohol rub (*n* =102)
No growth or scanty growth (< 20 colonies)	16	51	91
Moderate growth (20-100 colonies)	136	44	5
Heavy growth (> 100 colonies)	52	7	0

Data source: Maliekal, M et.al (2005) Indian J Crit Care Med. Vol 9(3).

(a) Did the two treatments reduce bacterial contamination?

(b) Which treatment was most effective:

(c) What evidence supports your choice?

(d) Repeat this experiment for yourselves. What did you find? Attach your results to this page.

5. Hong Kong is a densely packed region, with 7 million people within 1,104 km^2. In 1997, there was an outbreak of avian influenzavirus (bird flu) in Hong Kong. All 18 humans infected had been in recent contact with live domestic fowl (e.g. chickens) in markets. Six of the 18 infected people died. Authorities ordered the slaughter of all live chickens within Hong Kong (1.6 million birds) and stopped the import of more birds. No further cases of bird flu in humans were reported.

(a) Health authorities suspected that the chickens were the source of the virus. Based on the information above decide if you think they were correct in their hypothesis and explain your reasoning:

(b) Based on the evidence, do you think that the large scale slaughter of chickens and the ban on bird imports were justified? Explain your reasoning:

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Appendix

Questioning terms in biology

The following terms are often used when asking questions in examinations and assessments.

Analyse:	Interpret data to reach stated conclusions.
Annotate:	Add brief notes to a diagram, drawing or graph.
Apply:	Use an idea, equation, principle, theory, or law in a new situation.
Calculate:	Find an answer using mathematical methods. Show the working unless instructed not to.
Compare:	Give an account of similarities between two or more items, referring to both (or all) of them throughout.
Construct:	Represent or develop in graphical form.
Contrast:	Show differences. Set in opposition.
Define:	Give the precise meaning of a word or phrase as concisely as possible.
Derive:	Manipulate a mathematical equation to give a new equation or result.
Describe:	Define, name, draw annotated diagrams, give characteristics of, or an account of.
Design:	Produce a plan, object, simulation or model.
Determine:	Find the only possible answer.
Discuss:	Show understanding by linking ideas. Where necessary, justify, relate, evaluate, compare and contrast, or analyse.
Distinguish:	Give the difference(s) between two or more items.
Draw:	Represent by means of pencil lines. Add labels unless told not to do so.
Estimate:	Find an approximate value for an unknown quantity, based on the information provided and application of scientific knowledge.
Evaluate:	Assess the implications and limitations.
Explain:	Provide a reason as to how or why something occurs.
Identify:	Find an answer from a number of possibilities.
Illustrate:	Give concrete examples. Explain clearly by using comparisons or examples.
Interpret:	Comment upon, give examples, describe relationships. Describe, then evaluate.
List:	Give a sequence of answers with no elaboration.
Measure:	Find a value for a quantity.
Outline:	Give a brief account or summary. Include essential information only.
Predict:	Give an expected result.
Solve:	Obtain an answer using numerical methods.
State:	Give a specific name, value, or other answer. No supporting argument or calculation is necessary.
Suggest:	Propose a hypothesis or other possible explanation.
Summarise:	Give a brief, condensed account. Include conclusions and avoid unnecessary details.

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