CHAPTER 01

Biology keystones — Foundation skills

Learning outcomes

The development of a set of key science skills is a core component of the study of VCE Biology and applies across Units 1 to 4 in all areas of study. Chapter 1 scaffolds the development of these skills. The opportunity to develop, use and demonstrate these skills in a variety of contexts is important ahead of undertaking investigations and when evaluating the research of others.

Although this chapter can be read as a whole, it is best to refer to it and use it when the need arises as you work through other chapters. For example, you may need a refresher on the process of the scientific method. It also contains useful checklists to assist when drawing scientific diagrams, graphing and completing aspects of your report. Similarly, when performing a first-hand investigation, refer to this chapter to make sure you collect data properly and that your data is of high quality.

Key skills

Develop aims and questions, formulate hypotheses and make predictions

- determine aims, hypotheses, questions and predictions that can be tested
- identify independent, dependent and controlled variables

Plan and undertake investigations

- determine appropriate type of investigation: conduct experiments (including use of controls); solve a scientific or technological problem; use of databases; simulations; access secondary data, including data sourced through the internet that would otherwise be difficult to source as raw or primary data through fieldwork, a laboratory or a classroom
- select and use equipment, materials and procedures appropriate to the investigation, taking into account potential sources of error and uncertainty

Comply with safety and ethical guidelines

- apply ethical principles when undertaking and reporting investigations
- apply relevant occupational health and safety guidelines while undertaking practical investigations, including following relevant bioethical guidelines when handling live materials

Conduct investigations to collect and record data

- work independently and collaboratively as appropriate and within identified research constraints
- systematically generate, collect, record and summarise both qualitative and quantitative data

KEY SKILLS CONTINUED

Analyse and evaluate data, methods and scientific models

- process quantitative data using appropriate mathematical relationships and units
- organise, present and interpret data using schematic diagrams and flow charts, tables, bar charts, line graphs, ratios, percentages and calculations of mean
- take a qualitative approach when identifying and analysing experimental data with reference to accuracy, precision, reliability, validity, uncertainty and errors (random and systematic)
- explain the merit of replicating procedures and the effects of sample sizes in obtaining reliable data
- evaluate investigative procedures and possible sources of bias, and suggest improvements
- explain how models are used to organise and understand observed phenomena and concepts related to biology, identifying limitations of the models

Draw evidence-based conclusions

- determine to what extent evidence from an investigation supports the purpose of the investigation, and make recommendations, as appropriate, for modifying or extending the investigation
- draw conclusions consistent with evidence and relevant to the question under investigation
- identify, describe and explain the limitations of conclusions, including identification of further evidence required
- critically evaluate various types of information related to biology from journal articles, mass media and opinions presented in the public domain
- discuss the implications of research findings and proposals

Communicate and explain scientific ideas

- use appropriate biological terminology, representations and conventions, including standard abbreviations, graphing conventions and units of measurement
- discuss relevant biological information, ideas, concepts, theories and models and the connections between them
- identify and explain formal biological terminology about investigations and concepts
- use clear, coherent and concise expression
- acknowledge sources of information and use standard scientific referencing conventions.

1.1 The scientific method

Biology is the study of living organisms. As scientists, biologists extend their understanding using the scientific method, which involves investigations that are carefully designed, carried out and reported (Figure 1.1.1). Well-designed research is based on a sound knowledge of what is already understood about a subject, as well as careful preparation and observation.

FIGURE 1.1.1 Biological research may employ diverse approaches and procedures, such as molecular biology. Analysis of DNA extracted from feathers by scientists at the Museum of Western Australia has confirmed that the night parrot (*Pezoporus occidentalis*) is not extinct, as previously thought.

OBSERVATION

Observation includes using all your senses and a wide variety of instruments and laboratory techniques to allow closer observation. Through careful inquiry and observation you can learn a lot about organisms, the ways they function, and their interactions with each other and the environment. For example, animals clearly function very differently from plants. Animals usually move around, take in nutrients and water, and often interact with each other in groups. Plants, however, are green, stationary, turn their leaves towards the light and grow. Many other distinguishing macroscopic structures and behaviours can be discerned from simple observation. Microscopic observation of cells reveals similarities and differences in the cellular structure of plant and animal cells, as well as the specialisations in the cells of a particular organism. Observational studies are a common research method, but they do not explain all the details of how organisms function.

First-hand investigations

The idea for a first-hand investigation of a complex problem arises from prior learning and observations that raise further questions. For example, indoor plants do not grow well in the long term without artificial lighting, which suggests light is required for photosynthesis in plants (Figure 1.1.2). This aspect of photosynthesis can be researched and the new knowledge applied to other applications, such as methods for growing plants in the laboratory for genetic selection and modification for crop improvement.

FIGURE 1.1.2 Laboratory methods such as plant tissue culture rely on careful observations and data collection about the requirements for growth of plants in natural conditions. Laboratory investigations then provide new information that can be applied to plants growing in the field.

Interpreting observations

How observations are interpreted depends on past experiences and knowledge, but to enquiring minds they will usually provoke further questions such as:

- How do organisms gain and expend energy?
- Are there differences between cellular processes in plants, animals, bacteria, fungi and protists?
- How do multicellular organisms develop specialised tissues?
- What are the molecular building blocks of cells?
- How do species change and evolve over time?
- How do cells communicate with each other?
- What is the molecular basis of heredity and how is this genetic information decoded?

Many of these questions cannot be answered by observation alone, but they can be answered through scientific investigations. Many great discoveries have been made when a scientist has been busy investigating another problem. Good scientists have acute powers of observation and enquiring minds, and they make the most of these chance opportunities, like Alexander Fleming did when he discovered penicillin.

● *You will now be able to answer Key Question 1.*

BIOLOGY IN ACTION

Observation and discovery

Scottish physician Alexander Fleming was growing cultures of *Staphylococcus* bacteria in his laboratory in the 1920s (Figure 1.1.3a). Some of the agar plates he was growing the bacteria on became contaminated with a fungus called *Penicillium notatum*. From his observation that the bacteria were unable to grow in the region around the contaminating fungus, Fleming inferred that the fungus was releasing a substance that killed the bacteria. Experiments followed that used extracts from the fungus, and when a paper disc was soaked in this extract and applied to an agar plate culture of *Staphylococcus*, a clear zone appeared around the disc (Figure 1.1.3b). The bacteria could not grow in this area, demonstrating the antibacterial properties of this substance. Fleming named it penicillin after the type of fungus producing the chemical.

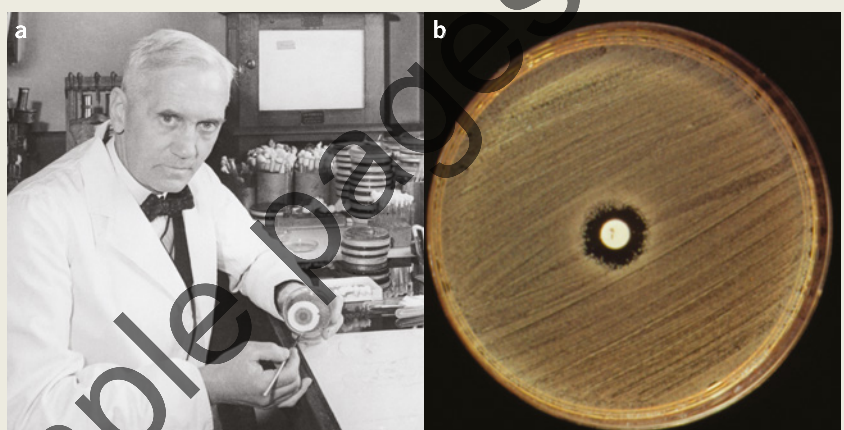


FIGURE 1.1.3 (a) Scottish biologist Alexander Fleming. (b) A culture of *Staphylococcus aureus* bacteria with a white disc containing penicillin placed at the centre. *Staphylococcus aureus* has not been able to grow near the penicillin disc.

After Fleming made the initial key observation that led to the discovery of naturally occurring antibiotics, the Australian scientist Howard Florey (then working at Oxford, England) and his colleagues further developed the methods for extracting penicillin on a large scale, and showed it was effective against staphylococcal and pneumococcal infections. Following the success of penicillin, pharmaceutical companies searched for other naturally occurring antibiotics, many of which were found in fungi (Figure 1.1.4).

FIGURE 1.1.4 An agar plate with fungal colonies. Many naturally occurring antibiotics now used as medications were discovered by studying fungi.

LEARNING BY EXPERIMENTATION

Scientists observe, study what is already known, and then ask questions. Using their knowledge and experience, scientists suggest possible explanations for the things they observe. A **hypothesis** is a possible explanation to a research question that can be used to make predictions, which can often be tested experimentally. This is the basis of the **scientific method** (Figure 1.1.5).

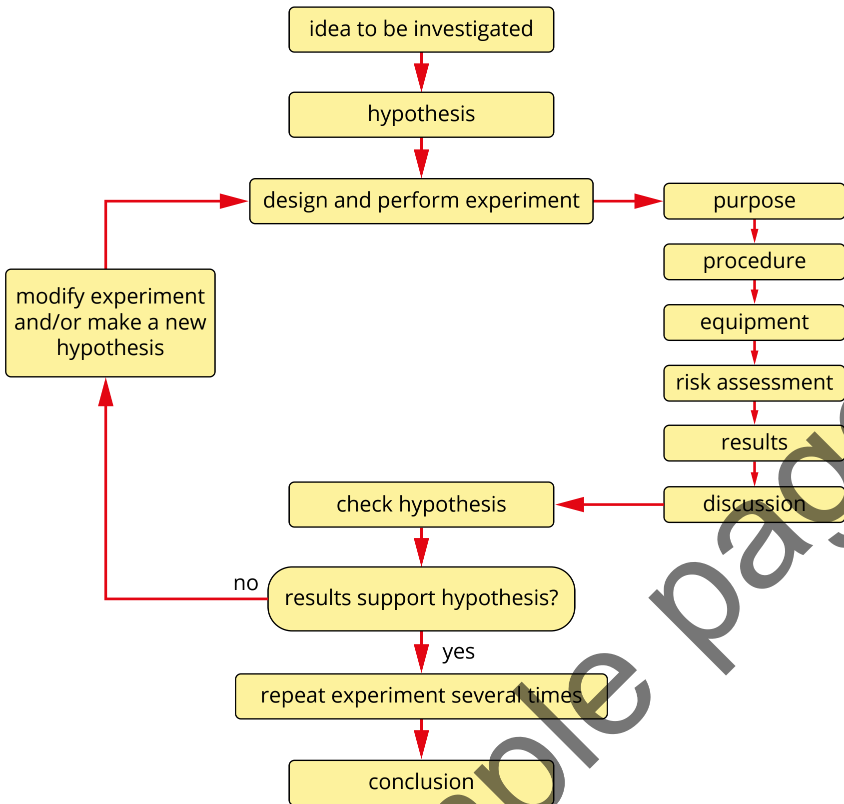


FIGURE 1.1.5 The scientific method.

Carefully designed experiments are carried out to determine whether the predictions are accurate or not. If the results of an experiment do not fall within an acceptable range, the hypothesis is rejected. If the predictions are found to be accurate, the hypothesis is supported. If, after many different experiments, one hypothesis is supported by all the results obtained so far, then this explanation can be given the status of a **theory** or **principle**.

There is nothing mysterious about the experimental approach to the study of science that is called the scientific method. You might use the same process to find out how an unfamiliar machine works if you had no instructions. Careful observation is usually the first step.

● *You will now be able to answer Key Question 2.*

ASKING THE RIGHT QUESTIONS

In science, there is little value in asking questions that cannot be answered. An experimental hypothesis must be testable, but your inability to test a particular hypothesis does not mean that the hypothesis cannot be correct.

Your ability to test a hypothesis may be limited by the resources and equipment you have available. If you ask a research question, form and test your hypothesis, and find your hypothesis is supported, that does not mean it is true in all circumstances. Likewise, if your hypothesis is not supported, that does not mean it is never true.

For example, you might hypothesise that 'Hydrogen peroxide is a toxic by-product of respiration that is broken down by catalases. As all eukaryotes undergo respiration they will all contain catalase'. However, there may be a eukaryote that lacks catalase, but testing every eukaryotic organism would be impossible, and just because a eukaryote without catalase hasn't been identified does not mean none exist.

- *You will now be able to answer Key Question 3.*

HAVING A GOOD METHOD

Methods must be described clearly and in sufficient detail to allow other scientists to repeat the experiment. If other scientists cannot obtain similar results when an experiment is repeated, then the experiment is considered unreliable. It is also important to avoid personal bias that might affect the collection of data or the analysis of results. A good scientist works hard to be objective (free of personal bias) rather than subjective (influenced by personal views). The results of an experiment must be clearly stated and must be separate from any discussion of the conclusions that are drawn from the results.

In science, doing an experiment once is not sufficient. You can have little confidence in a single result because you cannot be sure that the result was not due to some unusual circumstance that occurred at the time. The same experiment is usually repeated a number of times over a period of time and the combined results are then analysed statistically. If the statistics show that there is a low probability (usually less than 5%, referred to as $p < 0.05$) that the results could have occurred as a result of chance, then the result is accepted as being significant.

- *You will now be able to answer Key Question 4.*

THE NEED FOR EXPERIMENTAL CONTROLS

It is difficult—sometimes impossible—to eliminate all **variables** that might affect the outcome of an experiment. In biology, time of day, temperature, amount of light, humidity, and unidentified infections in organisms are examples of such variables. A way to eliminate the possibility that random factors affect results is to set up a second group within the experiment (called a **control group**) that is identical in every way to the first group (the **experimental group**) except for the single experimental variable that is being tested. This is a controlled experiment, because it allows you to examine one variable at a time. Controlled experiments are an important way of testing your hypothesis.

> The experimental conditions of the control group are identical to those of the experimental group, except that the variable of interest (the independent variable) is also kept constant.

> In an experiment, controlled (fixed) variables are kept constant; only one variable (the independent variable) is changed, and the dependent variable is measured to determine any effect of the change. Experiments and their results must be able to be repeated by other scientists to be validated.

The variable that the experimenter is testing is the **independent variable**.

The **dependent variable** is what is measured when the independent variable changes. All of the other factors that could vary but must be kept the same in all experimental groups are called **controlled variables**.

- *You will now be able to answer Key Question 5.*

When investigating antibacterial activity of compounds extracted from fungi or other sources, the variables to consider include the source, purity and concentration of the extract, the composition and consistency of the agar plates, the type of bacteria tested, the amount of substance on the test disc, the thickness of the discs and the incubation temperature. The independent variable would be the extract being tested. The dependent variable would be the presence and size of the zone of inhibition around the disc. The other variables listed above all need to be controlled. In Section 1.4 you will learn about setting up an investigation with controls.

MAKING VALID CONCLUSIONS

Conclusions are based on results and other knowledge. Making valid conclusions depends on the reliability of results and whether they are correctly interpreted. Speculation involves going beyond the results to make suggestions about what might be occurring. Conclusions are necessary, but speculation is interesting and thought-provoking. Both concluding and speculating are worthwhile, but you must be careful to keep them separate. It is also the usual practice of scientists to accept the simplest hypothesis that accounts for all the evidence available.

The conclusion made by Fleming, that *Penicillium notatum* produced a substance that can kill bacteria, was valid. It has been repeated many times and the principle generalised to the search for other antibiotics in a range of fungi and other organisms including bacteria and plants.

Experiments and their results must be able to be repeated by other scientists to be validated.

BIOFILE

Detecting antibiotic resistance

The conclusion made by Fleming was valid and led to the development of standard operating procedures for detecting antibiotic sensitivity and resistance in bacteria. If a bacterium is susceptible to an antibiotic, its growth around a disc containing the antibiotic is inhibited and observed as a clear zone on the agar plate, called the zone of inhibition. The greater the zone of inhibition, the more sensitive the bacteria are to the antibiotic. If a bacterium has developed resistance to an antibiotic it can grow around its antibiotic disc. Sometimes there is still a small zone of inhibition, but the bacteria are not sensitive enough for the antibiotic to be effective, so they are still considered to be resistant (Figure 1.1.6). The spread of antibiotic resistance by gene transfer between different species of bacteria is an important healthcare problem today. In 2015, the World Health Organization endorsed a global action plan to tackle antimicrobial resistance.

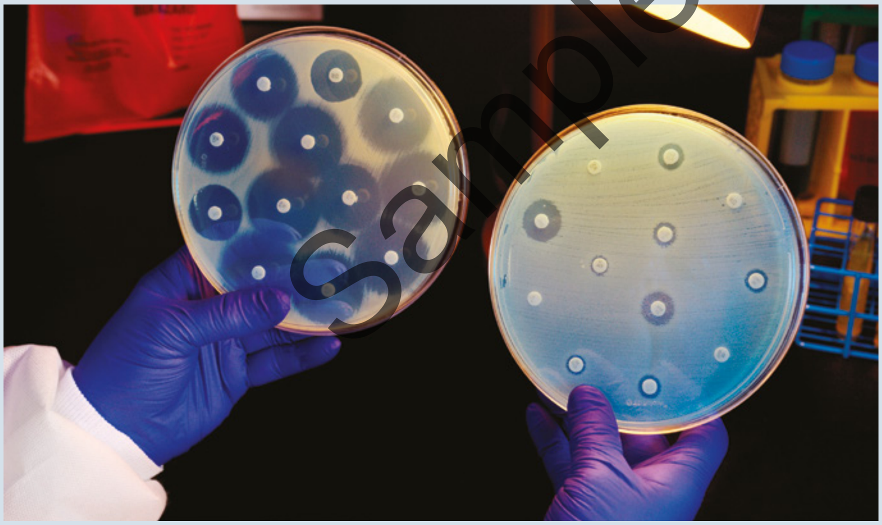


FIGURE 1.1.6 A microbiologist holding two Petri dish culture plates growing bacteria in the presence of discs containing various antibiotics. In the left plate bacteria are not growing around the discs because they are susceptible to the antibiotics on the discs. The plate on the right was inoculated with a carbapenem-resistant Enterobacteriaceae (CRE) bacterium that proved to be resistant to, and therefore able to grow well around, all of the antibiotics tested. Photographed at the Centers for Disease Control (CDC), USA.

LIMITATIONS OF THE SCIENTIFIC METHOD

The scientific method is not perfect; however, it remains the best way to understand our surroundings, and to constantly improve on that understanding. Even when the scientific method is strictly adhered to, there is still an element of chance in scientific discovery.

The scientific method can be applied only to hypotheses that can be tested, and to questions that can be answered. A hypothesis that is not testable can be neither supported nor disproved by the scientific method. Such hypotheses therefore remain as possible explanations. For example, Fleming's observation led to the hypothesis that certain fungi can produce chemicals that inhibit the growth of certain bacteria. This was testable for *Penicillium* and other fungi that can be grown on agar plates in the laboratory. If the hypothesis was broadened to 'All fungi produce antibiotics', this might not be testable, as it depends on being able to grow all fungi and all potential bacterial targets in the laboratory to test this hypothesis.

It is also important to understand that although science can prove a particular hypothesis wrong, it cannot prove that hypothesis to be true in all circumstances—only under the conditions that have been tested.

The scientific method cannot be used to test morality or ethics. These judgements belong to the fields of philosophy, history, politics and law. Science can, however, provide valuable information that people can take into account when making these judgements. For example, science can be used to predict the environmental consequences of pollution and the medical consequences of chemical weapons, but it cannot itself make value or moral judgements about either.

EXPERIMENTATION

Once you have a testable hypothesis, you are ready to conduct an experiment to test it. Every experiment has to be designed and planned carefully. You need to be sure that someone else can repeat your experiment exactly the way you did it and get similar results. In Section 1.2 you will learn how to formulate your hypothesis and design an experiment to test it.

● *You will now be able to answer Key Questions 6 and 7.*

MODELS

Scientific models are used to create and test theories and explain concepts. They may also be developed as prototypes for functional devices such as replacement organs. The introduction of computer technology, including two- and three-dimensional animations, has helped to create more detailed and realistic representations of biological processes. Different types of models can be used, but each model has limitations on the type of information it can provide.

Modelling concepts

Models are created to answer specific questions or demonstrate specific processes. How a model is designed will depend on its purpose. The two most familiar types of models are visual models and physical models, but mathematical models and computational models are also common and increasingly important in the biosciences. Models help to make sense of ideas by visualising:

- objects that are difficult to see because of their size (too big or too small) or position, such as ecosystems, organs such as the heart and pancreas, cells, molecules and atoms
- processes that cannot easily be seen directly, such as digestion, feedback loops, biochemical reactions, gene expression and protein folding
- abstract ideas such as energy transfer and the particulate nature of matter
- complex processes such as networks of biochemical reactions, genome organisation and regulation, evolution, and brain connectivity and function.

For example, models of all the connections between neurons in the human brain have been constructed from brain scanning technology. The models are used to predict and test signalling and communication between neurons (Figure 1.1.7).

Using digital modelling software to develop physical or mathematical models has enhanced our understanding in many areas. For example, dissection and surgical simulations can replace the practice of dissecting living organisms. As another example, computational modelling enables scientists to handle the huge amounts of data, such as that generated by genome sequencing.

A deeper understanding of concepts can be developed through models. However, you need to identify the benefits and limitations of using a particular model to represent a concept. Furthermore, the quality and validity of a model is limited by the depth and accuracy of the information used to construct the model.

FIGURE 1.1.7 A model of the brain's wiring pattern explored in the Human Connectome Project.

Visual models

Visual models are used to represent concepts. Diagrams and flow charts are examples of visual models (Figure 1.1.8). Computer animations of these structures and processes can give a more dynamic view.

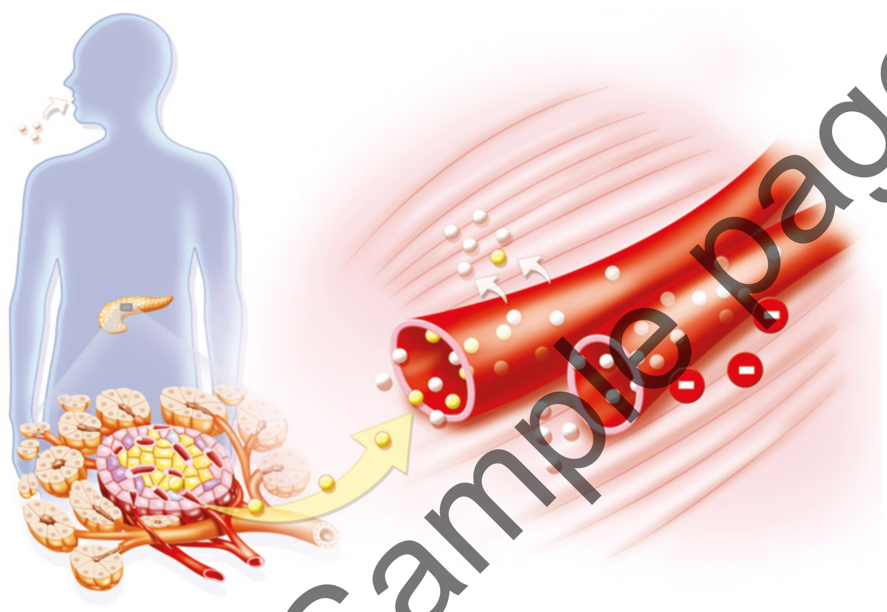


FIGURE 1.1.8 A diagram of a human body with a pancreas, showing aspects of internal structure and an indication of the organ's function, is an example of a visual model. This visual model of the human pancreas has multiple levels of detail. It illustrates the location in the body, the external structure of the organ and its internal cellular architecture, including the islets of Langerhans. It also represents functional elements, in this case release of the hormone insulin from islet beta cells into the blood. Insulin is a signalling molecule that promotes cellular glucose uptake and metabolism.

Physical models

Physical models can be scaled-up or scaled-down three-dimensional versions of reality. You have probably already used physical models many times in the classroom without being aware of it. The human skeleton is a physical model often seen in classrooms.

Although models help us to understand concepts, they are limited in how well they can represent what they are modelling. For example, although a plastic model of a lung does inflate and deflate, it does not take in oxygen and release carbon dioxide, and it is hard and solid instead of soft and flexible.

When making physical models (Figure 1.1.9), it is important to consider what materials are used to represent reality, so that the model has fewer limitations. The materials you use to construct your model should relate to what you are modelling.

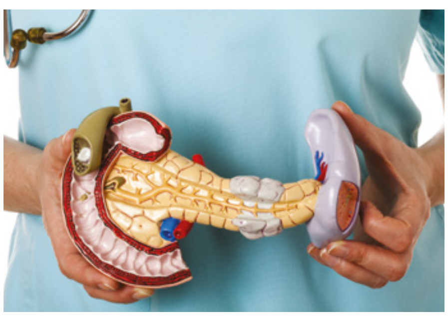


FIGURE 1.1.9 A physical model of a pancreas used in a clinical setting to help explain to a patient what is happening in that part of their body.

Computer and mathematical models

The complexity of biological systems has led to the use of mathematical modelling and computer simulations for testing hypotheses and conducting virtual experiments.

Computer simulations and mathematical models are being developed to model the complexity of whole cells, systems, organs or organisms, and allow virtual experimentation. Examples include:

- the bacterium *Mycoplasma genitalium* virtual cell
- connections between cells, for example all of the neural connections in the brain referred to as the connectome
- whole organs (virtual liver and heart)
- whole organisms such as the nematode worm *Caenorhabditis elegans*
- mathematical modelling of the way in which immune cells attack other cells
- gene interactions using data from the human genome project
- relationships between genotype and phenotype, using gene and protein sequence databases
- protein structure and function, using protein sequence databases and three-dimensional molecular modelling.

Bionic models

Physical models are often used as a prototype for developing replacement organs, such as prosthetic limbs. However, the complexity of biological systems limits the capacity of physical models to replace non-functioning organs. Research to make functional models focuses on single functions. Combining physical concepts with computer modelling of biochemical and physiological processes enables the development of models that mimic biological function.

For example, the pancreas is a complex organ with many different specialised cells and functions. Among these, it is the endocrine cells that detect blood glucose levels and release hormones to control blood glucose that are of interest when modelling diabetes. There is a bionic pancreas in development for the treatment of type 1 diabetes, which occurs when insulin-releasing beta cells are damaged. The bionic pancreas uses a glucose sensor to monitor blood glucose and a computer-controlled algorithm to direct the amount of insulin to be delivered by an insulin pump (Figure 1.1.10). Years of research and development are needed to gain enough understanding of the biological processes to develop such devices.

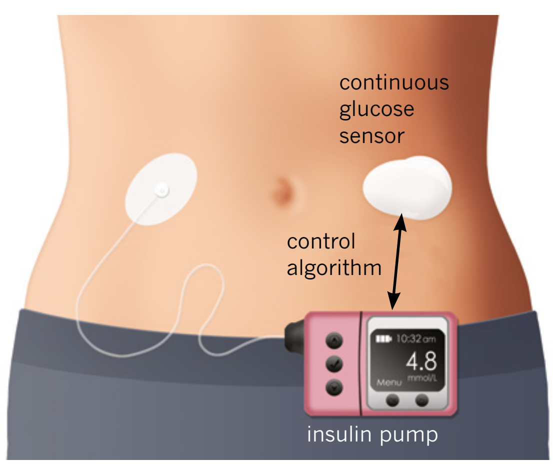


FIGURE 1.1.10 The components of a bionic pancreas developed for people with type 1 diabetes. A glucose sensor samples blood to measure blood glucose concentration. Computations determine whether a signal is sent to the insulin pump, which releases insulin when needed to maintain blood glucose in the normal range.

Model organisms

Biologists use live bacteria, animals and plants as model organisms for the investigation of cells and systems *in situ* and *in vivo*. It is possible to test hypotheses in animals that cannot be tested in humans for ethical reasons. Most of the advances in understanding animal and plant biology, genetics, pathology and medicine result from the use of model organisms. These organisms include the bacterium *Escherichia coli*, the nematode *Caenorhabditis elegans* (Figure 1.1.11), rats and mice, the plant *Arabidopsis thaliana*, and the vinegar fly *Drosophila melanogaster*.

Studies that are *in situ* are 'in position' or 'in place', such as when studying cells functioning within an intact organ, or molecules in their normal cellular location.

Studies that are *in vivo* are 'within the living', such as when cells are studied in a living organism.

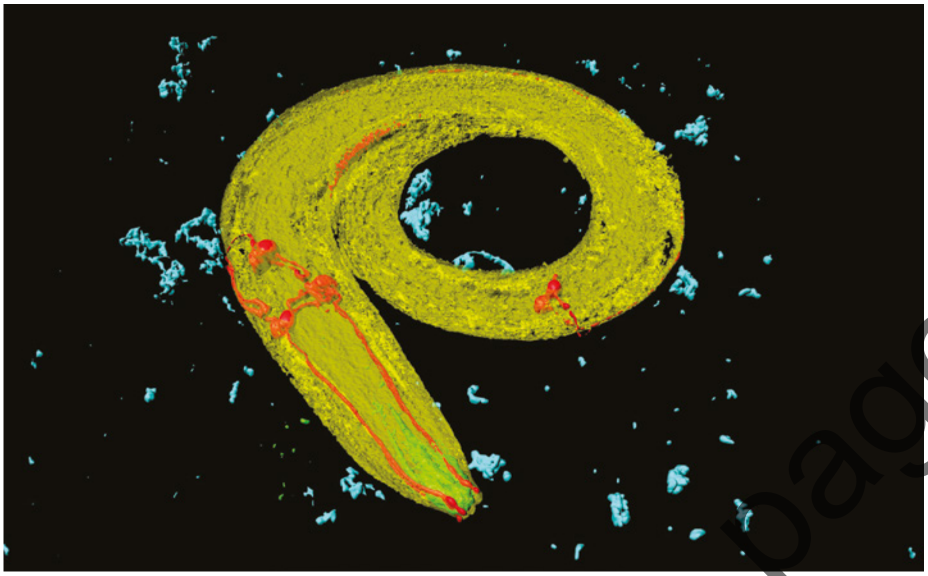


FIGURE 1.1.11 Model organism *Caenorhabditis elegans* worm. Confocal laser scanning micrograph of *C. elegans* with neurons stained green and the digestive tract stained red. *C. elegans* is a soil-dwelling nematode worm about 1 mm long and one of the most studied animals in biological and genetic research. A great deal is known about this organism, including its full genome, details of its life cycle, and the exact number of neurons in its nervous system (302) and how they form the nervous system.

Efforts are being made to reduce the number of animals used in research, and strict ethical guidelines must be followed in their use. Studies performed *in vitro*, and advances in computer simulation and 'virtual' cells and organisms that have made *in silico* studies possible, allow for a reduced reliance on live animals. But keep in mind that the value and validity of a virtual model or simulation is only as good as the data and information used to construct the model. This ultimately comes from living cells and organisms.

Studies that are *in vitro* are 'in glass' or in a dish or test tube, such as when cells are removed from the organism and studied in a culture dish (it doesn't have to be glass).

Studies that are *in silico* are 'in silicon', which refers to the silicon chips used in computers for computer simulations.

- *You will now be able to answer Key Questions 8–12.*

1.1 Review

SUMMARY

- Well-designed experiments are based on a sound knowledge of what is already understood or 'known' and careful observation.
- The scientific method is an accepted procedure for conducting experiments.
- A hypothesis is a possible explanation for a set of observations that can be used to make predictions, which can then be tested experimentally.
- Controlled experiments allow us to examine one factor at a time; they are the major means of testing hypotheses.
- Science can prove that a particular hypothesis is wrong, but it cannot prove it to be true in all circumstances.
- Science cannot be used to evaluate hypotheses that are not testable, nor can it make value or moral judgements.
- Models are useful tools that can be created and used to assist in a deeper understanding of concepts.

KEY QUESTIONS

1 The scientific method is a multistep process. Which two of the following are important parts of the method?

A observations made by eye and with instrumentation

B subjective decisions based on data collected

C careful manipulation of results to fit your ideas

D the use of prior knowledge to help objectively interpret new data

2 The following steps of the scientific method are out of order. Place a number (1–7) to the left of each point to indicate the correct sequence.

	Form a hypothesis
	Collect results
	Plan experiment and equipment
	Draw conclusions
	Question whether results support hypothesis
	State the biological question to be investigated
	Perform experiment

3 Scientists make observations and ask questions from which a testable hypothesis is formed.

a Define 'hypothesis'.

b Three statements are given below. One is a theory, one is a hypothesis and one is an observation. Identify which is which.

i If skin cells are exposed to UV light, cells will be damaged.

ii The skin burned when exposed to UV light.

iii Skin is formed from units called cells.

4 **a** What do 'objective' and 'subjective' mean?

b Why must experiments be carried out objectively?

5 Define 'independent', 'controlled' and 'dependent' variables.

6 **a** Explain what is meant by the term 'controlled experiment'.

b A student conducted an experiment to find out whether a bacterial species could use sucrose (cane sugar) as an energy source for growth. She already knew that these bacteria could use glucose for energy. Three components of the experiment are listed. Next to each one, indicate the type of variable described.

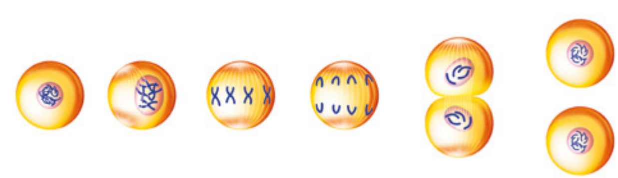
i presence or absence of sucrose

ii measurement of cell density after 24 h

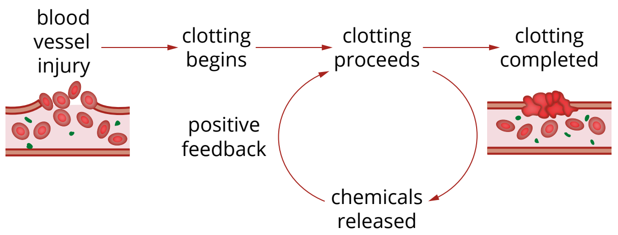
iii incubation temperature, volume of culture, size of flask

7 A scientist carries out a set of experiments, analyses the results and publishes them in a scientific journal. Other scientists in different laboratories repeat the experiment, but do not get the same results as the original scientist. Suggest several possible reasons that could explain this.

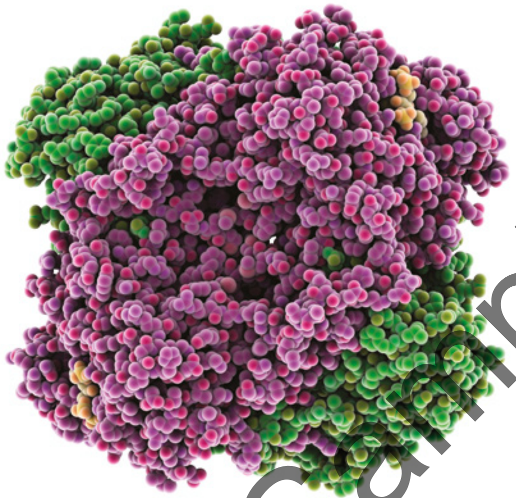
8 Explain what the visual model below represents.



9 The following diagram illustrates a body function involving a feedback loop. Describe what the model shows, and discuss the benefits and limitations of this diagram as a visual model of biological feedback.



10 Below is a molecular model of the enzyme catalase, which converts hydrogen peroxide to water and oxygen. Suggest reasons why scientists construct molecular models in addition to simple diagrams or a written description of its molecular composition.



11 Suggest some limitations of using models. Include examples.

12 Discuss how computer modelling could assist in representing scientific concepts and advancing scientific knowledge.