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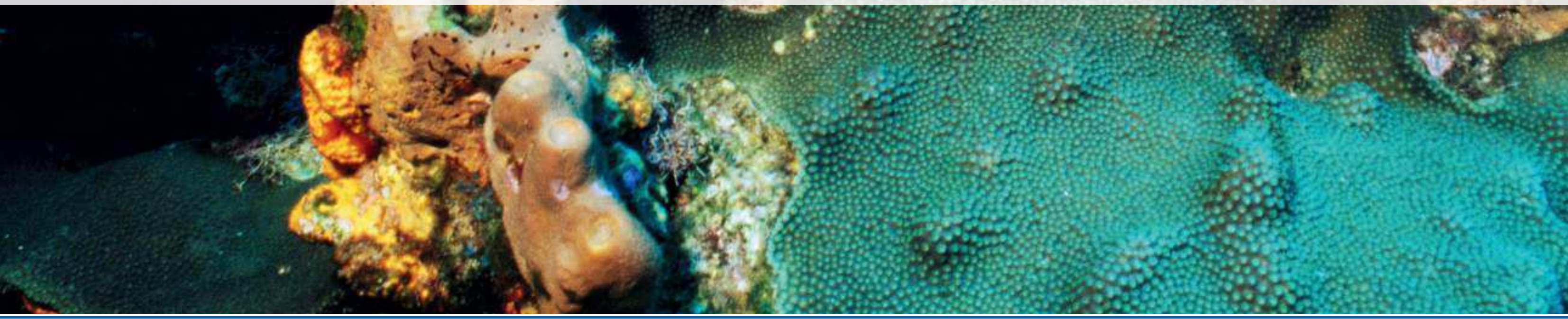
Chapter 1
Scientific method

Learning outcomes

By the end of this chapter, you should be able to:

- describe the steps in the scientific method
- explain how observations and questions are used to formulate a hypothesis
- use the scientific method to design experiments to test a hypothesis
- ensure that experimental results are valid by identifying independent, dependent and control variables
- explain how to make the results of an experiment reliable
- choose appropriate equipment to make accurate measurements and reduce the uncertainty in experimental results.



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1.1 The history of the scientific method

The Ancient Greek philosopher Aristotle is believed to be the first person who realised that it is necessary to take measurements in order to increase our knowledge. More than 2000 years have passed since he made this suggestion and scientific enquiry is still based on his idea. The philosophers and scholars who followed him added to his idea and refined it so that we now have a standard way to carry out scientific enquiry. In the Middle Ages a monk named Roger Bacon described a scientific method that he used to investigate nature. He made observations, formulated a **hypothesis** and carried out experiments. This sequence of events in scientific enquiry is probably familiar to most of us today. Galileo has been called the father of modern science and he also contributed to the development of the scientific method. He began to standardise measurements so that experimental results could be checked by other people.

The scientific method requires a logical approach in order to collect measurable results. Measurements are taken in an experiment designed to test a hypothesis. The results will then be used to either support or contradict the hypothesis. Because experimental data are naturally variable there will often be uncertainties in the results. The level of uncertainty can be reduced by ensuring that large numbers of accurate measurements are taken. **Variables** other than the one being investigated should be kept constant or, if this is not possible, measured. If enough evidence is gathered to support a hypothesis, then it may become a **theory**.

In this chapter you will begin to consider the use of the scientific method to formulate and test hypotheses. You will also learn how to plan controlled experiments to collect results to support or **refute** a hypothesis.

KEY TERMS

Hypothesis: an explanation of an observation that can be tested through experimentation

Variable: a condition in an experiment that can be controlled or changed

Theory: a well-substantiated explanation of an aspect of the natural world that has been repeatedly tested and confirmed through observation and experimentation

Refute (a hypothesis)**:** submitting evidence that shows that a hypothesis is not correct

1.2 Steps in the scientific method

There are several steps in the scientific method that should be followed whenever an experiment is planned (Figure 1.1). It is important to remember that the scientific method is a process. Even if a hypothesis is supported, ideas can change in the future if new observations are made.

Observations, questions and hypotheses

The first stage in the process is making observations. For example, you might observe that phytoplankton are found in the upper layers of the ocean. Initial observations are often **qualitative** rather than **quantitative**. This means that they are descriptive rather than having an amount or numerical value. In this case, the position of the phytoplankton is observed and its position in the ecosystem is described. A hypothesis is then formulated to try and explain the observation. A hypothesis is one possible answer to the question 'why?'. Your question might be: Why are the phytoplankton observed in the upper layers of the ocean? So your hypothesis could be that phytoplankton need light to grow. At this stage a **prediction** can also be made. A prediction states what you think will happen in the experiment and is linked to the hypothesis. To continue with the same example, your prediction might be: The more light phytoplankton are given, the more they will grow.

KEY TERMS

Qualitative data: descriptive data about a variable, for example colour or behaviour

Quantitative data: numerical data that give the quantity, amount or range of a variable, for example concentration of oxygen or number of eggs laid

Prediction: a statement of the expected results in an experiment based on the hypothesis being tested

Testing the hypothesis

The next stage is to design an experiment to test your hypothesis. The experiment needs to produce quantitative data that can be evaluated and used to support or refute (disprove) the hypothesis. All experiments involve variables:

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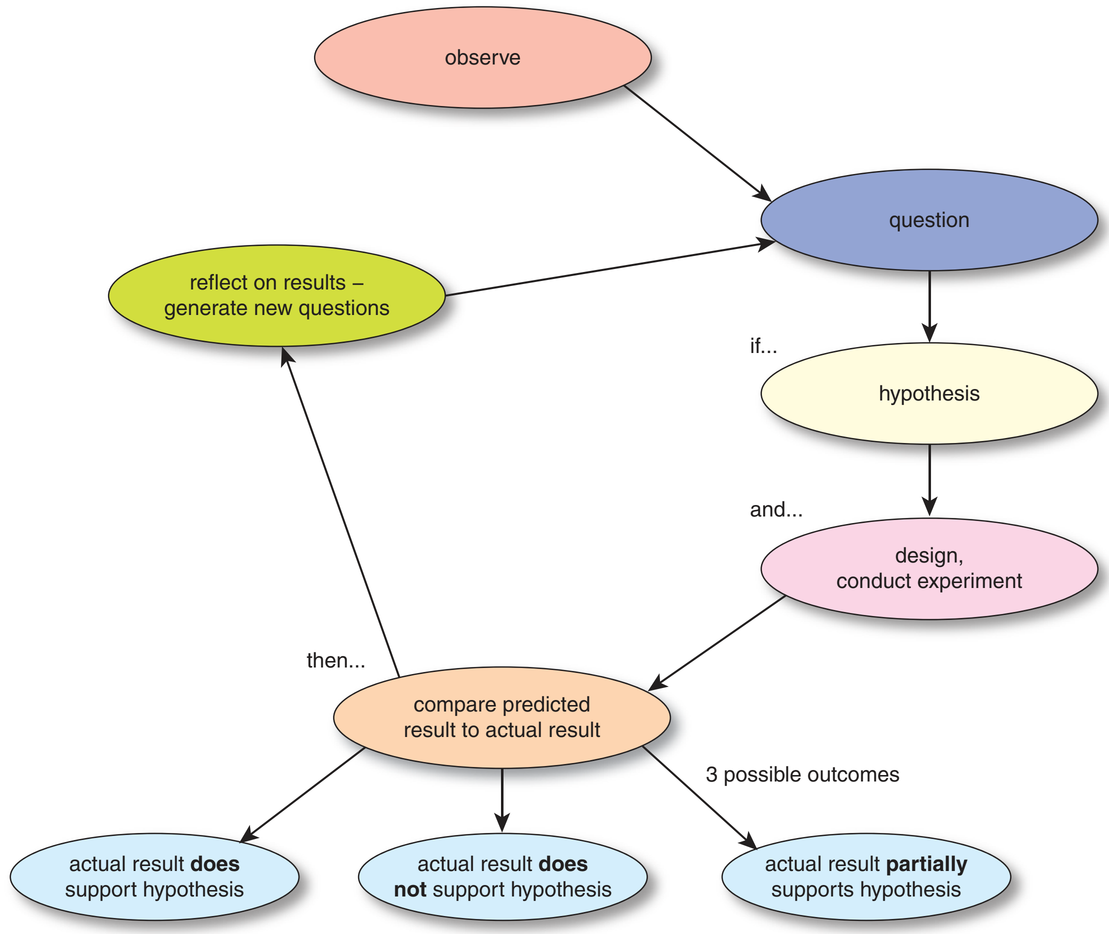

Figure 1.1. Steps in the scientific method.

these are the conditions that can be changed. The **independent variable** is the one that is changed during the experiment and the **dependent variable** is the one that is measured. To test your hypothesis that phytoplankton need light to grow you would need to change the light intensity. You would then measure the growth of the phytoplankton at different light intensities. This could be done by counting samples of the cells under a microscope.

KEY TERMS

Independent variable: the variable being changed in an experiment

Dependent variable: the variable being measured in an experiment

Control group: a group within an experiment or study that receives exactly the same treatment as the experimental groups with the exception of the variable being tested

Control variables: variables that are not being tested but that must be kept the same in case they affect the experiment

A **control group** should normally be included in the experiment. The control group is treated in the same way as the experimental groups apart from the independent variable. This gives you results to use as a comparison. If you are testing the hypothesis that phytoplankton need light to grow, the control group would be phytoplankton that are given no light. To obtain valid results, all variables other than the independent variable must be kept the same. If more than one variable is changed at the same time it would be impossible to say which one caused any changes in the measurements. The variables that are kept the same are the **control variables**. A control variable is any variable that could affect the dependent variable. Important examples to consider when deciding on the control variables are:

- temperature
- carbon dioxide concentration
- oxygen concentration
- pH

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- light intensity
- light wavelength.

Obviously these can only be controlled if they are not the independent variable and there may be other controls depending on the experiment being carried out.

It is much more difficult to control the variables in field-based experiments than in laboratory-based experiments. Clearly you cannot control the temperature or amount of light available on a seashore, for example. To help analyse the results, measurements should be taken of any variable that might affect the dependent variable. These are generally the same variables that would be controlled in the laboratory, for example the pH or light intensity. These are measured at the same sampling sites as the dependent variable and recorded. Any trends or patterns in the results can then be related to changes in these measurements as well as to changes in the independent variable. You may also see these variables referred to as **confounding variables**. A confounding variable is something that could affect the results of the experiment but that cannot be controlled.

To make sure that the results are **reliable** each treatment needs to be repeated. You can then calculate mean values for your measurements. It also allows you to identify any **anomalous** results that could affect your conclusions. Anomalous results are individual results that do not fit the pattern of the rest of the data. They may be caused by errors in measurement or difficulties in controlling the variables. It can be difficult to tell whether an anomalous result is due to natural variation within the variable being measured or genuine problems with the data. For this reason repeated readings are important to help to identify any anomalies by comparing them with the other readings taken at the same point in the experiment.

KEY TERMS

Confounding variable: a variable that could affect the dependent variable. In laboratory experiments these are the variables that must be controlled. In field experiments they are normally just measured and recorded

Reliable: results that can be replicated by other people

Anomaly: a result or observation that deviates from what is normal or expected. In experimental results it normally refers to one repeated result that does not fit the pattern of the others

SELF-ASSESSMENT QUESTIONS

1 Copy and complete Table 1.1 to summarise the different variables in an experiment.

type of variable	description
independent	
dependent	
control	
confounding	

Table 1.1. Types of variables.

2 A student observes that there are more algae growing in a fish tank in summer than in the winter. Suggest a hypothesis to explain this and predict the results of an experiment to investigate it.

Uncertainty in data

It is sometimes difficult to be certain about the results of experiments because the measurements will vary to some extent. If an experiment is reliable, it can be repeated by other people and similar results obtained. This decreases the uncertainty about the results. Controlling all variables apart from the independent variable also reduces uncertainty because you know that only the independent variable could have altered the measurements. Finally, all measurements must be taken as accurately as possible. This means choosing the most appropriate equipment to take the measurements and then reading the results properly. For example, when measuring liquids the **meniscus** is used. The meniscus is the curve in the upper surface of a liquid that is held in a container. A concave meniscus curves downwards and is seen when measuring the volume of water, for example. A convex meniscus curves upwards and is seen in mercury thermometers. In both cases it is the centre of the meniscus that is the point used to take the measurement. The meniscus must also be at eye level so that it can be read accurately (Figure 1.2). The correct equipment to measure a liquid is normally a measuring cylinder and the smallest appropriate size should be chosen. Measuring 8 cm^3 in a 10 cm^3 cylinder is more likely to be accurate than using a 200 cm^3 cylinder because it will be easier to read the correct value from the scale. For volumes of liquid that are less than 10 cm^3, a pipette or a syringe would be more accurate.

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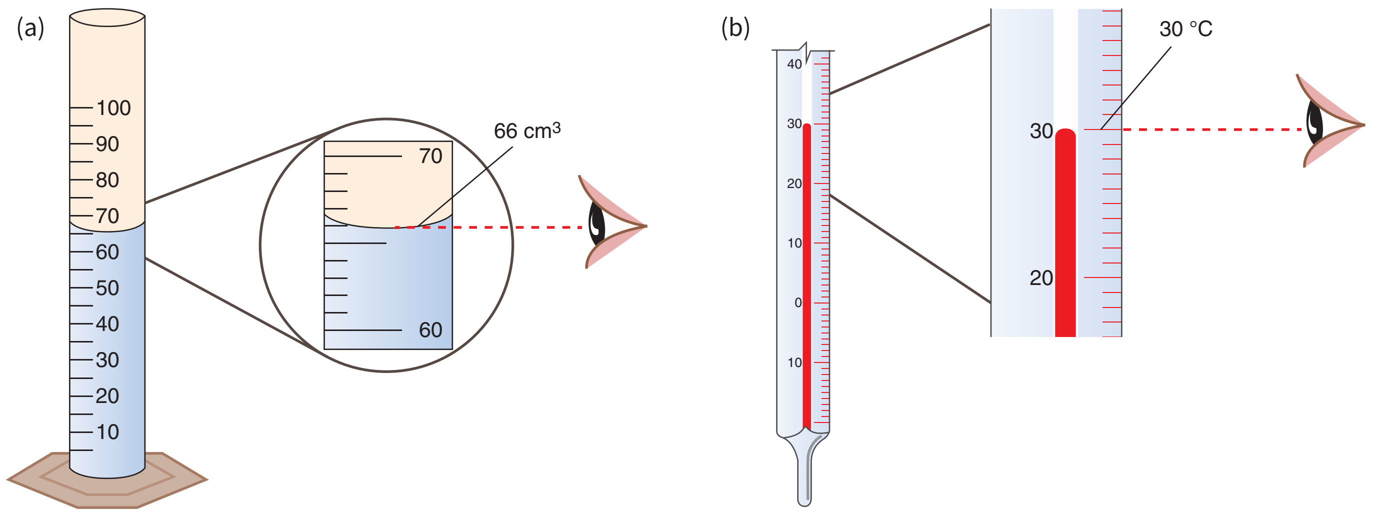

Figure 1.2. Reading the meniscus at eye level (a) in a measuring cylinder and (b) on a thermometer.

KEY TERM

Meniscus: the curve in the upper surface of a liquid inside a container. It is caused by surface tension and can be concave or convex

SELF-ASSESSMENT QUESTIONS

3 Suggest the most appropriate equipment to measure the following accurately.

- **a** 86 cm^3 of water
- **b** 0.5 cm^3 of water
- **c** The mass of seaweed found in 1 m^2

4 Figure 1.3 shows three measurements of volume being taken.

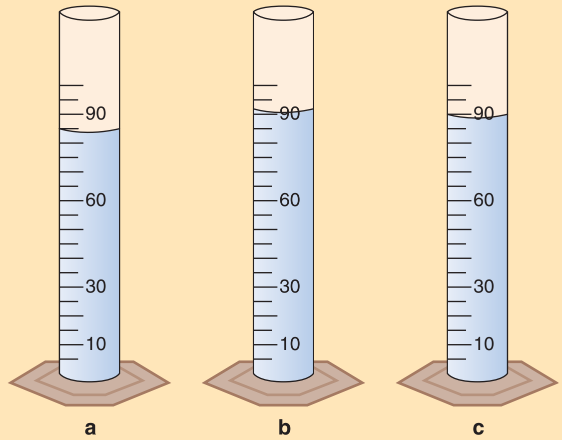

Figure 1.3. Three different measurements of the volume of liquids.

Describe how you would accurately read off the amount of liquid in each cylinder and write down the volume contained in each one.

Analysing the results

During any experiment, the results must be clearly and accurately recorded. The best way to do this is in a results table. This should be drawn before the experiment begins and must have space to fit in all the data to be collected. Normally, the independent variable is placed in the first column of the table. All the columns should have headings that describe the variables and state the units that will be used to measure them (Table 1.2).

light intensity / lux	number of algae present in sample after 2 days		
	trial 1	trial 2	trial 3
0			
2000			
4000			
6000			
8000			
10 000			

Table 1.2. A results table for an experiment investigating the effect of light intensity on the growth of algae.

The first stage in analysing the results is to calculate a mean from each set of repeated measurements. If one repeat is obviously different to the others and does not fit the pattern it may be an anomaly. Anomalies that have been caused by random errors in measurements can be ignored when calculating the mean. Standard deviation can also be calculated, which is a measure of the spread of data around the mean (see the Maths skills box in Chapter 10).

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The larger the standard deviation, the larger the range of the data. Percentages, rates and rates of change may also be calculated depending on the experiment (see the Maths skills box in Chapter 3). Often, a graph will be drawn to show the data more clearly and to see whether there is a relationship between the dependent and independent variables (see the Maths skills box in Chapter 4).

Once the data have been analysed a conclusion can be drawn. This should be a statement describing the results and any patterns obtained. The data obtained during the experiment are used to illustrate each point. The trends and patterns in the results should then be explained and linked back to the prediction. In general, the more accurate the measurements taken, and the less variation there is within repeated results, the more valid the conclusions will be.

A good conclusion will come from an experiment with the following features:

- repeated readings are taken
- anomalous results are identified and explained
- sufficient measurements of the dependent variable are made to show a clear pattern
- other variables are controlled and recorded
- the measurements of the variables are made accurately using appropriate equipment.

Evaluation of the hypothesis

If the results match the prediction, they support the hypothesis. If the results do not quite match the prediction, they do not support the hypothesis and it may need to be refined. If the results are completely different to the original prediction, they may be used to refute the hypothesis. This means arguing that the hypothesis is incorrect. You may then need to generate new questions by observing the data and making a new hypothesis that explains all of the data you now have. Alternatively, the original hypothesis may be refined to include the new observations.

SELF-ASSESSMENT QUESTIONS

5 Explain what an anomalous result is.

6 Describe the relationship between the prediction and the results if those results support a hypothesis.

1.3 Scientific theories

If a hypothesis is consistently supported by the results of many observations and experiments, it may become a scientific theory. Theories are intended to be accurate models of the world that can be used to predict what will happen in different situations. Theories can be modified as new observations and experimental data are collected. Examples of theories that are discussed later in this book are the theory of plate tectonics and the Darwin–Dana–Daly theory of atoll formation. Both of these theories started as hypotheses and only became theories when large amounts of evidence were found to support the original hypothesis.

1.4 Steps in planning valid laboratory-based experiments

Once a hypothesis and prediction have been made, an experimental approach to testing them must be planned. In order to obtain accurate results and to make valid conclusions, you should take the following steps.

1. Decide on the independent variable and the range of values to use.
2. List all the control variables that could affect the experiment and that must therefore be kept the same.
3. Decide how to keep the control variables the same.
4. Decide how many repeats to carry out.
5. Decide the timescale of the experiment.
6. Plan which measurements to take of the dependent variable and which equipment to use to do so accurately.

SELF-ASSESSMENT QUESTIONS

7 Distinguish between a hypothesis and a theory.

8 Suggest two control variables for each of the following investigations.

- **a** The effect of temperature on the growth of algae.
- **b** The effect of pH on the number of zooplankton.
- **c** The effect of light intensity on the growth of seagrass.

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Summary

- The scientific method is a series of steps that are used to investigate scientific phenomena.
- Observations are made first and used to formulate a hypothesis.
- A prediction is made based on the hypothesis.
- An experiment is planned to test the hypothesis by changing the independent variable and measuring the dependent variable.
- All other variables must be controlled in order to obtain valid results.
- There may be uncertainties in the results because of variability in the data and the accuracy of measurements.
- If the results match the prediction, they support the hypothesis.
- If the results do not match the prediction, they refute the hypothesis.
- A hypothesis that is supported by many sets of observations and experimental results may become a theory.

Exam-style questions

1 Design a laboratory-based experiment to test the hypothesis that algae need light to grow. **[6]**

[Total mark: 6]

2 An investigation into the growth of coral at different temperatures was carried out. Samples of coral were grown in the laboratory at different temperatures and the increase in surface area was measured in $cm^2\,week^{-1}$. The results are shown in Table 1.3.

temperature / °C	increase in surface area / $cm^2\,week^{-1}$			mean increase in surface area / $cm^2\,week^{-1}$
	trial 1	trial 2	trial 3	
14	0.3	0.5	0.2	0.33
16	0.6	0.6	0.8	
18	0.8	0.9	1.1	0.93
20	1.4	0.1	1.3	1.35
22	1.6	1.5	1.8	1.63
24	1.7	1.4	1.8	1.63

Table 1.3. Growth of coral at different temperatures.

a **i** Calculate the missing mean for 16 °C. **[2]**

ii Identify the anomalous result in the table. **[1]**

iii Describe the pattern shown by the results. **[2]**

b The researchers devised the following hypothesis to explain the results: Coral grows faster at higher temperatures.

i Explain whether the results support or refute the hypothesis. **[2]**

ii Give two factors that should have been controlled during the experiment. **[2]**

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c Design a laboratory-based experiment to investigate the effect of salinity on the growth of coral. **[6]**

[Total mark: 15]

3 A field-based experiment was carried out that investigated the distribution of two different species of fish in an estuary.

a Suggest three environmental factors that could affect the distribution of fish in an estuary. **[3]**

b These factors cannot be controlled during the experiment. Explain what should be done instead. **[2]**

[Total mark: 5]

CASE STUDY

Barnacle distribution

A student made the observation that two species of barnacle appeared to be distributed unevenly on a rocky shore. She noticed one species (*Chthamalus stellatus*) living nearer the high water mark than the other (*Semibalanus balanoides*). She decided to investigate her observation using the scientific method and so formulated a hypothesis. Her hypothesis stated that *Chthamalus stellatus* was more able to resist drying out than *Semibalanus balanoides* (Figure 1.4)

Figure 1.4. Barnacles growing on rocks.

She marked out a 50 mm^2 area just above the low-water mark and counted the number of each species that was present. She then repeated this at 5 m intervals from the low-water mark to the high-water mark at the top of the shore.

Her results are shown in Table 1.4.

distance from low water mark / m	number of *Semibalanus balanoides*	number of *Chthamalus stellatus*
0	12	0
5	9	8
10	11	0
15	6	0
20	0	10

Table 1.4. Distribution of two species of barnacle on the shore.

The student concluded that her results supported her hypothesis. Some of the other students in her class were not sure and argued that there were problems with her results and with her method.

Questions

1 State the independent and dependent variables in this investigation.

2 It is often difficult to control variables when not in the laboratory: suggest a variable that the student could have controlled.

3 Which result do you think is most likely to be anomalous and why?

4 Suggest what might have caused the anomalous result.

5 Suggest how the experiment could be improved.

6 Do you agree with her conclusion?

