

Nature of Science

Introduction

The word ‘science’ derives from the Latin *scientia*, meaning ‘knowledge’. Historically, the term has been particularly used to describe knowledge based on clear, reproducible evidence. The implication is that the resulting knowledge is reliable and objective, and might be used to make predictions. This essentially means that whatever is claimed to be true can be proven again (and again) in similar circumstances.

The modern term ‘science’ refers to a process of creating knowledge, rather than the body of knowledge itself, but the principles underlying the process are still related to the meaning of the original Latin term. Knowledge is created through a process that must be objective, based on evidence. Whatever knowledge is generated should be true irrespective of the context, circumstances and time. However, while the aim of science is to be objective, we shall see that it is not possible to completely disconnect the process from influences of culture, economics and politics.

The process of science is based on different methods of gathering evidence, including experimentation and observation. The methodology is designed to answer specific questions or test hypotheses (testable explanations), and it may make use of models. The data obtained may lead to the construction of theories and laws. But, while science is often seen as a strictly methodological process, scientists also have to be ready for unplanned, surprising or accidental discoveries – the history of science shows that this is a common occurrence – and working as a scientist therefore requires creativity and imagination as well as structured thinking.

A universal language would facilitate and support the process of science. Use of a single language would mean that scientists worldwide could agree on what is being discussed, without misunderstandings being introduced in translation. In fact, different ‘universal languages’ are used in different areas of science. For example, many aspects of physics and chemistry are expressed in mathematical notation, chemists use chemical equations and structural formulae, and Latin is used extensively in biology and medical sciences. Nowadays, the bulk of scientific literature is in English irrespective of the native language of the scientists or the country where the research was conducted or published.

It is important to recognise that science is a dynamic process: the understandings that underlie ongoing research evolve and develop, and theories may be falsified and replaced by newer ones. The general public often do not understand this aspect of science. Many people think that science is a fixed body of knowledge and, if they see that a theory is no longer accepted or is unable to explain recent findings, they conclude that ‘science’ is unreliable. However, it is precisely the dynamic nature of science that makes it reliable and trustworthy. It demonstrates a constant striving for the best possible description and explanation, and it guarantees that the ‘current’ theory describes a phenomenon as accurately as possible given existing knowledge. The nature of science is to renew itself constantly. It is an exciting and challenging adventure where the focus lies on searching for new knowledge.

The word **scientist** was first used in 1834 by naturalist and theologian William Whewell. Before that, people who studied the natural world were known as **natural philosophers**.

Scientists may work together with technologists to create new technologies but progress in technology can be limited by current scientific theory. This may then trigger further research to solve technological quandaries. Technology and science are closely linked, but technology requires scientific understanding in order to exist and develop.

This chapter will discuss many aspects of science. It will show, above all, that science is an exciting, human endeavour with all its fallacies, weaknesses and pitfalls. The strength of science lies in the underlying process which guarantees that truth will ultimately prevail.

This section covers:

- the purpose and processes of science
- obtaining evidence
- drawing conclusions – deduction and induction
- intuition and serendipity
- scepticism
- the language of science.

Other areas of applied science include:

- electronics
- food science
- forensic science
- environmental science.

1 What is science?

The purpose and processes of science

The nature of science is based on a number of **axioms**, or assumptions that are seen as self-evident. These assumptions are that:

- the Universe has a reality that is independent – in other words, the Universe exists whether or not we are there to see it
- this reality can be accessed by human senses or instrumentation and understood by human reason.

The main aim of **pure science** (or basic science) is to discover what that objective reality is. This is done by collecting evidence from which conclusions can be drawn about the nature of the Universe. These conclusions may in turn lead to more questions about the Universe, meaning that new evidence needs to be gathered to answer those new questions. In summary, the nature of science is to convert the concrete (observations) into abstractions (laws and theories).

Pure science has a different aim from **applied science**, which uses scientific understanding for a specific purpose. For example, pharmaceutical scientists use their understanding of the human body and of characteristics of certain chemicals to find new medicines. Both pure and applied science can in turn contribute to the fields of technology and engineering, which focus on using and improving tools and systems to solve practical problems. The boundaries between these various fields are not distinct, and insights in one field can frequently lead to progress in another.

It is sometimes suggested that there is a single **scientific method**, but this is not correct: different methodologies are required to obtain different kinds of evidence. The type of evidence needed will depend on the question that the scientist is trying to answer, and it will influence the way in which that evidence is interpreted and conclusions are drawn. However, there must be agreement among scientists as to what constitutes a scientifically valid method. After all, what value is a finding that has meaning to only one person? Findings must be the same universally, otherwise they cannot be said to be objective and independent. For this reason, many methods are standardised, and methods must be communicated in such a way that another scientist could follow the same method to reach the same conclusions.



Obtaining evidence

By **evidence** we mean data about the Universe that reveal something about its nature. Evidence can be gathered using the human senses, but instrumentation and sensors are increasingly employed. Using technology to gather evidence is a more objective method and can also allow gathering of evidence not accessible to human senses. Just think of measuring temperatures in nuclear reactors or gathering data at the bottom of the ocean near black smokers. Most of the evidence gathered in fields such as astronomy would also be impossible without the help of modern technological instruments.

Evidence can be obtained using three general methods.

- **Observations:** Galileo Galilei's observations of the moons of Jupiter at the beginning of the 17th century were important evidence against the theory that everything in the Universe orbits the Earth.
- **Experimentation:** Gregor Mendel's experiments in the 19th century in which he cross-bred pea plants led to important insights into the mechanism of heredity.
- **Modelling:** modelling the current motion of the galaxies has led to the conclusion that the Universe is 13.8 billion years old.

Evidence obtained through any of these methods can be used to support a claim about the nature of the Universe, and many established scientific theories have been built on a combination of evidence obtained from all three methods.

Observations

Observation is the direct recording of data about the Universe. It is important to realise that observation does not just include seeing things with our eyes. Observation also includes using other human senses and, increasingly, instrumentation and sensors.

Our understanding of naturally occurring events is largely based on observation: think, for instance, about observations of solar eclipses or the ongoing monitoring of the extent of sea ice in the Arctic. Scientists may also observe data that can lead to conclusions about processes that have happened in the past: for example, observations of existing organisms and those found in the fossil record informed the theory of evolution. But scientists also observe events that they bring about themselves in the laboratory: for instance, holding a sample of calcium in a flame turns the flame brick-red.

It is sometimes suggested that conclusions reached through observation of naturally occurring phenomena are less valid than those reached through experimentation (see below), but this is not true. As long as the process of reasoning is sound, the conclusions reached are valid. The subsequent discovery of further evidence to support these conclusions may further strengthen the conclusions.

Some areas of science depend to a great extent on observation. An obvious example is astronomy. Observations of the radiation emitted by distant galaxies, as well as the radiation that fills the Universe, lent support to the Big Bang theory for the origin of the Universe. This well-known theory became established through the power of observation combined with structured reasoning and elaborate modelling.

The Big Bang theory

When the Big Bang theory was developed, no controlled experiments were possible to support it because of the time spans and scale of the events. However, experiments at the Large Hadron Collider at CERN (*Conseil Européen pour la Recherche Nucléaire* – the European Organization for Nuclear Research) can now recreate conditions that might resemble the early Universe, albeit for a very short time, and can be used to test theories of what the Universe was like in its infancy.

Experimentation

Observation may lead to ideas or questions that can be studied through **experimentation**. An experiment is a test designed to answer a specific question – for example, about what happens in a particular process. In an experiment, the researcher performs certain actions and observes their effects. Thus, experimentation is, in effect, a specific form of observation. In an experiment, conditions are controlled so that the researcher can be sure that the effects observed are the result of the actions carried out.

One of the key uses of experiments is to establish cause and effect – in other words, to find out whether one variable or factor has an effect on another variable or factor. The principle of this type of experiment is highly standardised in science. The researcher will make changes to one variable (e.g. the temperature) and then measure a second variable (e.g. the rate of a chemical reaction). In this way, the researcher can determine how temperature affects the rate of this particular reaction. To be sure about this result, other variables that may affect the rate of reaction must be controlled. For example, in each test, the researcher would use the same concentrations of chemicals, and follow the same procedure of mixing, stirring and so forth.

Examples of famous science experiments

In 1747, James Lind added different foods to the diet of crew members on long sea voyages. The results showed that eating citrus fruit prevented the crew from getting a disease called scurvy, which was common among 18th-century seafarers, while cider, vinegar and sea water did not prevent the disease. We now know that scurvy is caused by a lack of vitamin C.

In 1909, Ernest Rutherford designed an experiment in which α -particles were fired at thin sheets of metal. Most of the particles passed through the films, but some were deflected (changed direction). To explain these results, Rutherford suggested that the atoms in the metal consisted of a dense core at the centre – the nucleus – surrounded by an area of mostly empty space.

Forecasting the weather

A prime example of the application of models is in weather forecasting. Many factors influence weather systems, such as changes in the jet stream, sea water temperature, carbon dioxide concentrations and solar output, to name but a few. Computer models harnessing all these data have significantly improved the accuracy of weather forecasts.

Modelling

An established theory can be used to formulate a **model**. A model is any representation of an object, concept or process. There are many different types of model. Some models help us to **visualise** processes. For example, a flow chart may be used to model the pathways in human metabolism to help us see how they interact. The Bohr model of the atom is an example of a model that offers a particular way of thinking about a concept. It does not describe the atom exactly, but it describes certain features in a way that explains particular properties, such as the absorption and emission of radiation by atoms.

Modern advances in computing power have allowed the development of elaborate mathematical and computational models, and these have had an immense influence and impact. Models have become powerful tools which are capable of predicting the precise outcome of certain experiments.



Drawing conclusions – deduction and induction

Given the same set of results and background information, all scientists should come to the same or similar conclusion. Their training gives them common reasoning skills of deduction and induction.

Deductive reasoning involves using a set of general statements or observations that we know to be true to reach a logically sound conclusion. It is a ‘top-down’ process – we use general truths to arrive at a conclusion. An example of this kind of reasoning goes as follows:

Statement: *Increasing nitrate concentration in the soil causes plants to grow faster.*

Statement: *Organism X is a plant.*

Conclusion: *Organism X will grow faster if the nitrate concentration in the soil is increased.*

Thus, deduction is a reliable way of arriving at a conclusion.

However, there are many situations in which we make an observation that we cannot explain using a set of general statements we know to be true, because we do not have enough prior knowledge. In those situations, we must use inductive reasoning. This is a ‘bottom-up’ process, which involves generalising from a few specific observations to reach a more general conclusion. An example of this type of reasoning is as follows:

Observation: *All swans we have seen are white.*

Conclusion: *All swans in the world are white.*

The conclusion above **could** be true because it fits the observations. However, as it turns out, there are also black swans. This is a problem with induction: just because an event has always been observed happening in a particular way, or every known example of a particular object has certain characteristics, does not necessarily mean that this event will always happen in this way or that these objects will all have these characteristics.

Induction is therefore a less reliable method of arriving at a conclusion that is true, but it can still be a useful way of thinking. It is common to begin reasoning through induction based on a small number of observations and then to find more evidence to support the initial tentative conclusion. Charles Darwin’s **theory of evolution** is a good example of this.

In the Galapagos Islands off South America in 1835, Darwin (1809–1882) observed that finches feeding on different foods had beaks of different sizes and shapes. He then used his observations to draw conclusions about the evolution of the birds’ beaks. He thought that the environment – the availability of a variety of food sources – must have had an impact on how the beaks of these finches changed over time. Natural selection would have ensured the survival and increased breeding success of those finches best suited to a particular food type, resulting in speciation (species formation). It is clear that this type of conclusion would need further evidence, but it was the inductive reasoning based on these first observations that led to the gathering of the huge body of evidence that now supports the theory of evolution.

Einstein's intuition

Albert Einstein (1879–1955) used his intuition to work out the basic concepts of relativity. Only later was he able to develop the mathematics necessary to express his ideas and predictions. It is interesting to note that some of his predictions were proven many years later – when Einstein's ideas were published, the technology and instrumentation did not exist to test his predictions.

Intuition and serendipity

The discussion so far may give the impression that science is always a methodical business, that conclusions follow logically from evidence, and that conclusions lead in a straightforward manner to new theories and areas of research. This is by no means always the case. Great leaps forward have been made thanks to **intuition**, speculation and creativity.

Another driver of scientific discovery is serendipity, or 'happy accident'. In the pursuit of new data, scientists can come across unexpected findings in their work in the lab or in the field which can lead to great discoveries. Perhaps the most famous example of scientific serendipity is the discovery of penicillin. Sir Alexander Fleming (1881–1955) left a Petri dish containing a culture of *Staphylococcus* sp. open by mistake. The bacterial culture was contaminated by a blue-green mould, which formed a visible growth and inhibited the growth of the bacterium. The mould was isolated and purified and found to belong to the *Penicillium* genus. Somehow this fungus could make and release a substance with antibacterial activity. This substance is now known as penicillin, and it has been one of the most important life-saving discoveries in medical history.

This example demonstrates that significant scientific discoveries can be a matter of luck. However, it still takes an astute and creative scientist to recognise what she/he observes and pursue it further. As the Hungarian biochemist Albert Szent-Gyorgyi (1893–1986) said: 'Research is to see what everybody else has seen, and to think what nobody else has thought.'

Scepticism

Science is a human endeavour and therefore errors due to human fallibility and subjectivity will inevitably occur. Experimentation or observations can lead to certain claims, but scientists should initially be sceptical. Any claim should be judged only once there is good reason to believe it to be either true or false, based on solid evidence and reasoning.

Unexpected findings have been known to lead to exceptional claims. The cold fusion claim is one notable example: nuclear fusion normally requires temperatures above 10 000 000 K, so the claim that fusion could be achieved at room temperature was extraordinary. With such highly controversial claims it is easy to remain sceptical. Most scientists would not immediately accept or dismiss such findings; they would either try to repeat the experiments or wait until other scientists published similar results. Few claims are as extraordinary as the cold fusion example, but nothing that a scientist publishes should be accepted without solid evidence and reasoning that put it beyond doubt.



Cold fusion

In 1989, Stanley Pons and Martin Fleischmann reported that they had achieved 'cold fusion'. They had designed a small table-top reactor in which they electrolysed heavy water on the surface of a palladium (Pd) electrode. Their apparatus produced excess heat, which could not be explained by the chemical process that took place in the reactor. The only explanation seemed to be in line with nuclear processes and, further to this, the team reported measuring small amounts of nuclear reaction by-products, including neutrons and tritium.

Other laboratories attempted to repeat the experiments of Fleischmann and Pons but to no avail. Their findings have never been corroborated and this area of research has now largely been abandoned.

See also: http://undsci.berkeley.edu/article/cold_fusion_01

(Note that this area of research should not be confused with muon-catalysed fusion, which is an established area of research.)

The language of science

It is of paramount importance that scientists should use a common language. Science is a global enterprise and it makes sense that results can be read, understood and used by everyone around the world.

Today, the vast majority of scientific proceedings and most scientific journals are published in English, and English has also become the standard language for international conferences and congresses. This communality facilitates collaboration between scientists of different nationalities.

In addition, scientists in certain fields have developed their own terminology, notations and other conventions to make sure that they can communicate unambiguously. Medical scientists and biologists heavily rely on Latin. The physical sciences have agreements about standard units – called SI units – and notations that are used as defined by the International Bureau of Weights and Measures (BIPM). Chemistry has adopted universally understood symbols to represent the elements, and the International Union of Pure and Applied Chemistry (IUPAC) is the accepted authority on the standardisation of chemical nomenclature.

Mathematics is a powerful tool for scientists that can be considered a language in itself. Many scientific ideas in disciplines such as physics can only be expressed mathematically.

BIPM: <http://www.bipm.org>

IUPAC: <http://www.iupac.org>

Learning objectives

This section covers:

- theories and paradigm shifts
- laws
- Occam's razor
- hypotheses and falsification
- correlation and cause.

2 Understanding of science

Theories and paradigm shifts

In science, a **theory** is defined as a comprehensive model of how a particular process or part of the Universe works. A theory may contain or be built upon definitions, facts, laws and hypotheses that have been tested.

The scientific meaning of the word 'theory' is therefore very different from the meaning it sometimes has in public understanding, referring to a vague, unsubstantiated idea. If something is referred to as a theory in science, there is no reason to doubt its validity. In fact, quite the opposite is true: established scientific theories are based on large bodies of evidence.

Examples of scientific theories

The theory of evolution describes how natural selection drives the change in inherited characteristics of living organisms over time. For example, it can predict what will happen to a bacterial population when it is subjected to the environmental presence of antibiotics. Natural selection will ensure that only those bacteria within the population that can enzymatically break down the antibiotics will survive. So the exposure to antibiotics drives the population to evolve antibiotic resistance and this feature is passed on to the offspring of those bacteria.

Isaac Newton's theory of gravitation reliably describes the gravitational pull that any two objects will have on each other, and it can be used to predict the behaviour of planets.

The atomic theory can be used to make predictions about the properties of substances on a macroscopic scale.

Understanding the cause of stomach ulcers

A good example of a paradigm shift is the acceptance of the cause of stomach ulcers. In the early 1980s, Barry Marshall and his co-worker Robin Warren (Nobel laureates in 2005) proved that the bacterium *Helicobacter pylori* could cause ulcers. It had previously been widely accepted that stomach ulcers could be caused by stress and other factors but not as a result of a bacterial infection. It took a long time before their theory was accepted in the scientific community.

While individual theories concentrate on well-defined areas of knowledge, there is overlap in the facts and assumptions incorporated into different theories. This means that scientific understanding comprises a coherent body of knowledge that hangs together in a consistent way. From time to time, however, new theories emerge that have widespread implications for other theories, causing a radical change in understanding. Such a change in understanding is called a **paradigm shift**; *paradigm* is the Greek word for 'pattern'. Paradigm shifts are part of the nature and strength of science, ensuring that scientific ideas always reflect the latest evidence.

The term 'paradigm shift' was first introduced by Thomas Samuel Kuhn (1922–1996), an American physicist, historian and philosopher of science, in his book *The Structure of Scientific Revolutions*, published in 1962. Kuhn stated that scientific knowledge progressed not in a gradual way but by periodic paradigm shifts. He described these shifts as 'universally recognised scientific achievements that, for a time, provide model problems and solutions for a community of researchers'. Thus, a paradigm shift represents a major move away from a previously held notion. It provides the scientific community with novel views, approaches and explanations which, up to that time, had been absent or in some cases might have been considered heresy.



Paradigm shifts do not necessarily make ‘old’ theories invalid. At the beginning of the 20th century, Albert Einstein’s theory of relativity represented a paradigm shift relative to Newtonian mechanics. However, Newtonian mechanics are still perfectly applicable in many situations. Here, the new paradigm offers a deeper and wider understanding, but it does not make the old paradigm obsolete.

Laws

In science, a **law** is a statement that describes a particular behaviour. Laws are derived from repeated observations or experiments and often describe a relationship between two or more variables. A law states that the same result or phenomenon is always observed under the same conditions, and it can therefore be used to make predictions. Because laws need to be universal and should be easily understood across languages and cultures, they are often expressed as mathematical formulae or equations.

Note that, in contrast to a theory, a law does not **explain** a phenomenon, it only **describes** one.

Examples of scientific laws

- **Newton’s second law** states that the acceleration of a body is proportional to the net force on the body and inversely proportional to the mass of the body. This is expressed mathematically as $F = ma$.
- **The law of conservation of mass** states that the amount of matter does not change in a chemical reaction – there will be the same amount of matter after the reaction as there was before it.

Occam’s razor

In formulating a law or theory, a scientist should strive for the simplest form that fits the available evidence. This essentially means that the simplest explanation for a phenomenon is assumed until further evidence suggests that a more complicated explanation is needed. This principle is known as **Occam’s razor**, attributed to William of Occam (c.1287–1347), a philosopher and theologian.

As an example, let us imagine that a scientist has conducted an experiment on the effect of nitrate concentration on the growth of plants. The results show that nitrates cause plants to grow faster. The scientist could now start to formulate a theory about the relationship between the growth of plants and nitrates. The simplest explanation is that the nitrates are absorbed by the plants and used in a way that is beneficial to their growth. A more complicated explanation might be that the nitrates are poisonous to worms, that the lack of worms causes the population of moles to decline, and that the absence of moles means that there is less damage to plant roots, allowing the plants to grow better. Both of these explanations fit the observation, but the simpler explanation should initially be used to guide further investigations into the exact effect of nitrates on plants.

Falsifiability

Sir Karl Popper (1902–1994), an Austro-British philosopher of science, alleged that falsifiability marks the boundary between science and pseudoscience (see Section 5). He argued that research findings based on an unfalsifiable hypothesis could only be considered pseudoscientific and thus could not be taken as reliable.

Hypothesis or law?

A hypothesis may look similar to a law, but it is important to recognise that the two are very different. A hypothesis forms the basis of an investigation and can be rejected on the basis of a single experiment. A law has been established through repeated observations or experiments, and it forms part of accepted scientific understanding.

Hypotheses and falsification

Scientific knowledge develops through the testing of hypotheses. A **hypothesis** is a testable statement or prediction. A scientist may formulate a hypothesis based on an idea they have about how the world works, for example based on particular observations or prior experiments. The hypothesis is then tested through experimentation.

Hypotheses should be formulated so that they are **falsifiable**. This means that the hypothesis must be phrased in such a way that an experiment can be designed to prove it wrong. The following example will illustrate this.

Suppose that a team of scientists has observed that, in a paddock, plants located closer to an area where cows frequently urinate grow larger than those in other areas. Urine contains urea, a nitrogen-based compound which can be converted to nitrates by nitrifying bacteria. Based on these observations, the scientists might propose that nitrate positively influences the growth rate of plants. They might propose the following hypothesis:

Increasing nitrate concentrations in the soil increases the growth rate of plants.

Note that the hypothesis is a statement, not a question.

Is this hypothesis testable? Yes it is, because we can design an experiment in which we vary the nitrate concentration and measure the effect on plant growth rate. Is the hypothesis falsifiable? Yes, because if plants do **not** grow faster in soil with higher nitrate concentration, the hypothesis will be proven wrong.

Note also that it is not possible to prove that a hypothesis is true, only that it is false. Here, we can show that increasing nitrate concentrations in the soil increases the growth rate of plants **in this particular study**, but that does not guarantee that it is always true. This is the induction problem (see Section 1). The hypothesis can, however, be supported if the same effect is observed over and over again, and if a plausible mechanism is found for how nitrates might stimulate plant growth.

The scientific process can be summarised as follows.

- A scientist will use inductive and deductive reasoning based on observations and/or experimentation to arrive at certain conclusions.
- He or she may then begin to formulate a theory.
- This theory needs to be tested; the scientist proceeds by formulating hypotheses.
- Experimentation based on these hypotheses will yield further observations and conclusions.
- The evidence found by the scientist will give rise to further (testable) questions, which will lead to further experimentation.

In real laboratory life, this process may take many years and involve many people, since each of the steps sometimes requires difficult and lengthy experiments. However long it takes, it brings us full circle and demonstrates how science progresses in a dynamic and developmental way.

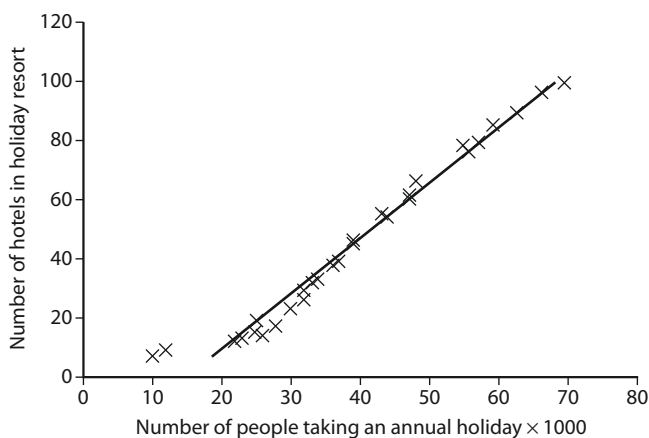


Figure 1 This graph shows a positive correlation. If more people take a holiday in a resort, then that resort will have more hotels.

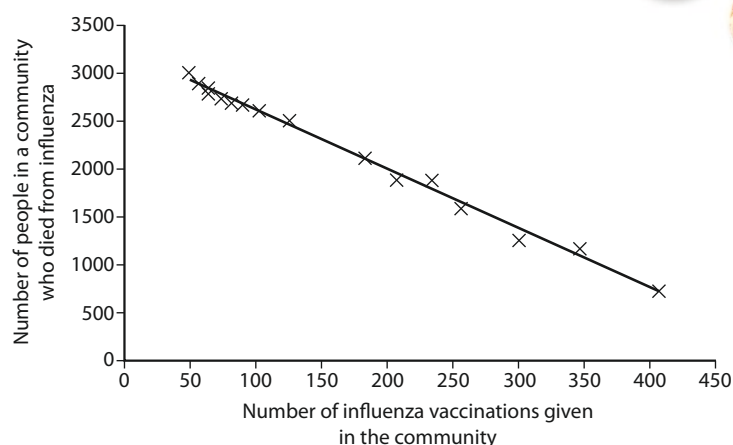


Figure 2 This graph shows a negative correlation. In communities where more people were vaccinated against influenza, fewer people died from the disease.

Correlation and cause

Correlation is a reliable statistical link between two variables. This means that, as one variable increases, the other variable either also increases (positive correlation, Figure 1) or decreases (negative correlation, Figure 2).

It is important to realise that, while a strong correlation between two variables may suggest that there is a causal relationship (i.e. that a change in the first variable directly causes a change in the second), this is not necessarily the case. For example, look at the graph in Figure 1. It could be that increases in the number of holidaymakers in certain resorts caused more hotels to be built there. However, the reverse could also be true: holidaymakers could be attracted to certain resorts because they have a lot of hotels.

Observation of a correlation therefore often warrants further studies to establish **causation**. The best way to establish causation is through a carefully controlled experiment in which the effect of altering one variable is measured, but this is not always possible. For example, if a study has shown a positive correlation between eating fried food and getting bowel cancer, it would be unethical to feed different groups of people different amounts of fried food and see how many develop bowel cancer. So, other methods are sometimes needed.

One way of supporting the case for a causal relationship is to propose a plausible mechanism by which one variable could have an effect on another. For the fried food/bowel cancer example, a plausible mechanism might be that certain chemical compounds in fried food cause DNA mutations in cells in the bowel. These mutations may involve genes that suppress cancer. These events, combined with a weakened immune system and other genetic factors, may lead to bowel cancer. This is a complex picture, but it is possible to carry out experiments to establish parts of the mechanism. For example, chemicals from fried foods can be added to human bowel cells *in vitro*, to see if the cells turn cancerous.

Other methods used to obtain evidence for causal relationships in medical studies include sampling, cohort studies, case control studies, double-blind tests and clinical trials. All of these are basically surveys with large numbers of people (patients) with similar backgrounds, diets, age and so on, so that as many variables as possible are controlled. Statistics (see Section 3) are an indispensable tool for the analysis of these data.

The term *in vitro* is Latin for 'in glass'. It is used to describe studies carried out on parts of organisms outside the living organism. Studies on living organisms are termed *in vivo*, which means 'within the living'.

This section covers:

- qualitative and quantitative data
- repetition and replication
- errors
- statistics
- cognitive bias
- outliers
- databases.

3 Objectivity of science

Qualitative and quantitative data

Data, or evidence, can be in two basic forms: quantitative and qualitative.

Quantitative data are based on measurable quantities and are therefore numerical. They are measured using tools or instrumentation yielding values with (standardised) units. For example, the temperature of a reaction mixture (in °C) or the volume of gas produced in a chemical reaction (in cm³) constitutes quantitative data.

Qualitative data deal with apparent or implicit qualities and are expressed in words. They are usually observations, made either in an experiment or from an examination of something. The following are examples of qualitative data: 'the reaction mixture turned cloudy'; 'when the two objects collided, a loud noise was heard'; 'this type of insect lifts its wings when threatened'.

Quantitative data are usually objective and more suitable than qualitative data for accurately describing phenomena and making predictions. Because they are numerical, quantitative data can be mathematically analysed to establish links between variables and to identify patterns. On the other hand, qualitative data are seen as more subjective, and the research for this type of data gathering is far more difficult to repeat or confirm. This is not to imply that qualitative research is not valid, but it is less likely to yield theories or laws that are applicable to all humanity or valid throughout the whole Universe. That is why scientists prefer to rely on quantitative data.

Repetition and replication

Science and data are inextricably linked. Data need to be reliable so that realistic and trustworthy predictions can be made, and the reliability of data can be improved by making repeated measurements.

It is therefore good practice for scientists to take repeated measurements, by performing the same experiment multiple times. If an experiment is **reproducible** (i.e. it gives the same result each time it is repeated), then we can have confidence in the results. If the values measured in each experiment are close together, then we say the measurements have high **precision** (see below).

In addition to scientists repeating their own results, it is also important that results are **replicated** by other scientists in different settings. If the results cannot be replicated, this might mean that there was an error inherent in the original procedure (see below), leading to false results. Replication is important to show that results are **accurate**, that they are a true reflection of reality. Figure 3 illustrates the difference between precision and accuracy.

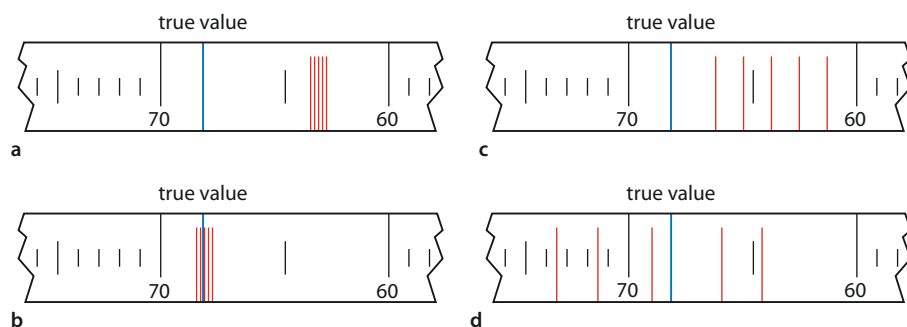


Figure 3 The difference between precision and accuracy. Results are shown in red and the true value measurement is indicated in each diagram by a blue line. The results in **a** have high precision (they are close together) but low accuracy (they are not close to the true value of the measurement). The results in **b** have high precision and high accuracy. The results in **c** have low precision and low accuracy. The results in **d** have low precision and high accuracy (because the mean value is close to the true value). Despite the high accuracy, this last set of results would still be considered poor data.

Some large experimental set-ups, such as the Large Hadron Collider (LHC) in Geneva, Switzerland, generate vast amounts of data which are difficult to interpret. In order to increase the reliability of these data, it makes sense to replicate the experiments, but that is a costly affair. The LHC therefore has replication built in: it has multiple detectors. The detectors perform the same experiments but they are run by different groups so, when they produce the same result (such as identifying the Higgs boson), we know that the result is reliable.

Errors

However carefully an investigation is carried out, it is always possible for errors to occur. Scientists must have an in-depth understanding of how and why errors occur and must consider to what extent any errors may have affected the data. Errors mean that quantitative data are not always as objective and accurate as one might think, but careful experimental design can reduce the number and impact of errors. For example, temperatures read off an analogue mercury thermometer may vary slightly depending on who takes the measurement. However, if a digital thermometer is used, the readings should all be the same. Scientists therefore rely heavily on equipment to record data. Any measuring or recording equipment used needs careful calibration to ensure that the readings are accurate and standardised, but built-in errors may still exist.

There are two main types of error: random and systematic.

- **Random errors** are caused by variables that cannot be controlled and by limitations in the measuring apparatus. For instance, if you are using a balance to measure a mass of sodium chloride, random errors in the measurement might be caused by the movement of air in the room or by friction between the mechanical parts of the balance.
- **A systematic error** is a bias in measurement that is inherent in a procedure or measurement. For example, you might measure the mass of sodium chloride using a balance that has not recently been calibrated and that consistently records a mass that is 1.00 g too high.

The two types of error affect measurements in different ways. Random errors will affect each measurement differently. The value recorded may be higher or lower than the actual value, and the difference from the actual value may be large or small. The repeated measurements will be randomly

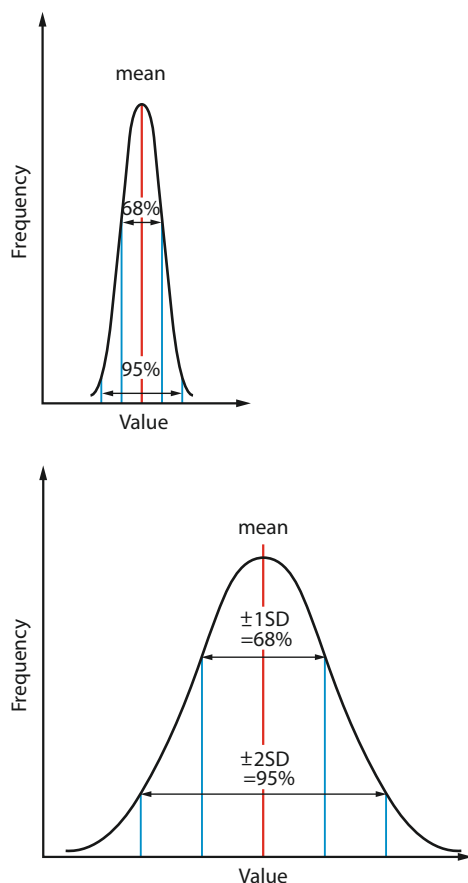


Figure 4 Two different normal distribution curves. A normal distribution is tall and narrow if the data values are close together, and flat and wide if the values are more spread out. In all cases, 68% of values fall within 1 standard deviation (± 1 SD) of the mean, and 95% of the values fall within 2 standard deviations.

Chi-squared test

The chi-squared test is used to evaluate the outcomes of genetic cross-breeding experiments. Scientists look at the appearance of certain characteristics in successive generations of an organism. They then compare those results with the results they would expect to see if the characteristics had a particular genetic basis. This can rule out or support hypotheses about the genetic basis for characteristics.

distributed around the actual value. The result is that random errors affect **precision**, or how close together repeated measurements are (see Figure 3). This means that the presence of random errors is quite easy to spot – they cause a spread in values for repeated measurements.

Conversely, systematic errors always affect measurements in the same way. If an instrument is calibrated incorrectly, it will consistently give measurements that are the same amount higher or lower than the actual value. Therefore systematic errors affect the **accuracy** of the measurements, or how close they are to the true value (see Figure 3). Systematic errors are fairly easy to spot if a literature value exists for a particular measurement but they can be much harder to spot if there is no accepted value. This is one of the reasons that it is so important that studies are replicated by other groups.

Statistics

Since errors are impossible to avoid, scientists rely on **statistics** to get a better understanding of what a ‘normal’ range is and which values are to be considered ‘outliers’ or false readings. Statistics is a branch of mathematics that concerns itself with the collection, presentation and interpretation of data, and statisticians have developed tools that help scientists to predict and assess the validity of comparing sets of data.

Statistics facilitate the summarising of large sets of data. Among other things, statistics make use of three forms of average – the mean, median and mode – each of which conveys a different aspect of the data set. The **mean** is a mathematical value obtained by dividing the sum of a set of values by the number of values in the set. The **mode** is the most frequently occurring number. The **median** is the middle value when all values are ranged in order. Different situations may require the use of different averages.

It is often found that data form a **normal distribution** (Figure 4). In a normal distribution, the measured values are distributed evenly around a central, most probable, value and the mean, mode and median values are all the same. The **standard deviation** (SD) is an indication of the spread of the data around the mean value in a normal distribution (Figure 4). If a series of repeat measurements has a high SD, this means that there is a wide spread in the data, indicating that the measurements have low precision.

There are many statistical tests that help scientists to establish whether correlations exist between variables. We can use the **chi-squared test** to compare observed data with data that we would expect to see if a certain hypothesis were true. If there is a significant difference, this proves the hypothesis false. A **t-test** is widely used to assess whether two sets of data are statistically different from each other, based on the means and standard deviations of the two data sets. Imagine, for example, that a road tyre company wants to know if their new tyre gives shorter stopping distances under braking. They will make repeated measurements (in controlled conditions) of stopping distances using the new and the old tyre. A *t*-test will show whether there is a statistical difference in stopping distance between the two tyres.

Levels of confidence

A **level of confidence** is an indication of how sure the scientist is that a true value lies in a particular interval. For example, a report might state that the concentration of arsenic in a sample of drinking water is $0.072\text{--}0.081\text{ mg dm}^{-3}$ with a level of confidence of 95%. This means that, according to the statistical calculations, we can be 95% sure that the true value of the concentration lies within that range or **confidence interval**.

The confidence interval can be calculated for any level of confidence, although 95% is common. The range of the confidence interval is an indication of the precision of the measurement. Repeating the experiment can reduce the range of the confidence interval.

Error bars and best-fit lines

When scientists depict data in graph form, error bars and best-fit lines are often displayed as well. An **error bar** is a vertical line drawn through a data point and it indicates the variability for that point. It can display the range (the minimum and maximum values measured), the standard deviation or the confidence interval for a particular confidence level. This allows other scientists to assess objectively if the data presented indeed give rise to the conclusions. For example, if the error bars between two data points do not overlap, this is a good indication that they are significantly different. Figure 5 shows what error bars look like. In this case, we can be more confident about the accuracy of the third data point than that of the first or second, because the error bar is shorter.

Best-fit lines are used to make the interpretation of a graph easier. They are widely used in scatter graphs where two variables are plotted against each other. The patterns that arise are often difficult to interpret so a best-fit line can highlight a trend. Figure 6 shows two examples of best-fit lines; note that the best-fit line is not necessarily a straight line – the form of the line depends on the relationship between the variables.

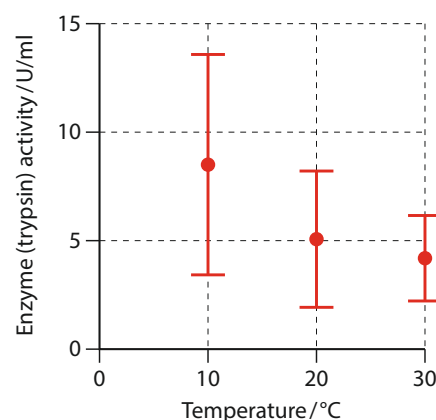


Figure 5 Error bars give an idea of the variability of the measurements obtained. In this graph of trypsin activity versus temperature, the error bar for the third data point is the shortest, which means that this value is likely to be more accurate than the other two.

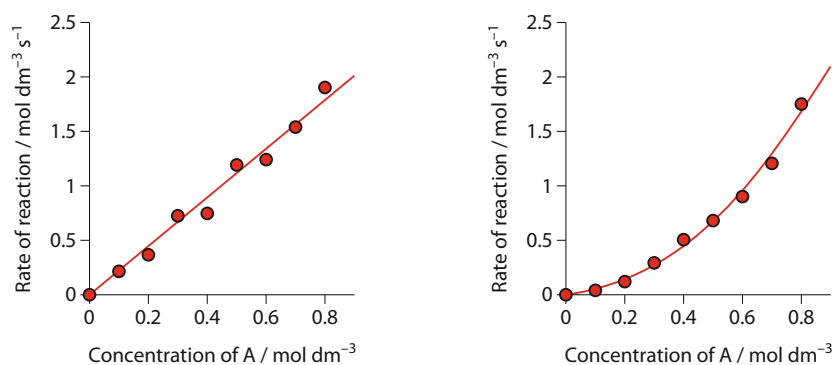


Figure 6 Best-fit lines on graphs measuring rates of reaction.

A best-fit line should be drawn so that the total distance between the data points and the line is as small as possible. A best-fit line allows other scientists to assess the data objectively and adds to the reliability of the data.

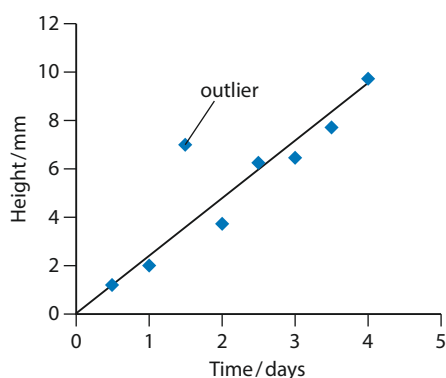


Figure 7 Drawing the best-fit line through this graph showing the growth of alfalfa seedlings makes it obvious that one of the data points is an outlier.

Examples of scientific databases

There are a large number of DNA sequence databases, many of which can be searched through the **National Center for Biotechnology Information (NCBI)** website: <http://www.ncbi.nlm.nih.gov/nuccore>

Online Mendelian Inheritance in Man (OMIM) is an online database with information on the majority of inherited diseases: <http://www.ncbi.nlm.nih.gov/omim>

The **CERN** website provides updates in the field of nuclear physics: <http://home.web.cern.ch/>

Chemical Abstracts Service (CAS), a division of the American Chemical Society, is the world's authority for chemical information: <http://www.cas.org/>

Cognitive bias

Cognitive biases are ways in which we tend to make errors of judgement in different situations. Scientists need to be aware of biases that might affect how they interpret results, so that they do not come to the wrong conclusions.

An important bias to recognise is **confirmation bias**. This is the tendency to dismiss or disagree with information that does not fit with our understanding or theories, and to favour information that agrees with what we already thought.

Imagine, for example, that a scientist obtains a set of results that confirm his favourite theory, but he hears about a different group which has obtained results that deny the theory. He may try to find errors in the other group's results to show why they are wrong but may not consider whether similar errors might exist in his own data. Alternatively, another scientist may have produced an unexpected result that does not fit with anything she has seen before. She may easily dismiss it as an error, but it is possible that this is an important new finding. These are instances of confirmation bias.

Outliers

When taking measurements, it is common for some findings to seem to be well outside the normal range. Scientists call these data **outliers**. These are often caused by random errors but, in some cases, such results are true findings, indicating that there is a larger range than expected.

Figure 7 shows an outlier in a set of results. The graph seems to confirm that most data points lie in the range of 0 to 4 (x-axis points) with values of between 0 and 10 (values on the y-axis). The data point at 1.5 on the x-axis is much further from the best-fit line than the rest of the data points, indicating that it does not fit with the expected model or theory. It is understandable, when encountering such a finding, to dismiss it as an outlier.

But should we always discard outliers? In nature, exceptions are not uncommon, therefore outliers and unexpected findings are not particularly unusual. Sometimes they can lead to new discoveries, theories and models, so scientists should remember the existence of confirmation bias and pay special attention to these 'flukes'. They must maintain a balance between healthy scepticism and too readily accepting their own favoured theories. In the example in Figure 7, the correct course of action would be to repeat the experiment, to find out if the outlier is a true result.

Databases

In some areas of science – for example, meteorology and particle physics – scientists have to analyse thousands or even millions of sets of data. The huge increase in computing power over recent decades has allowed this. In more and more areas of science, data are being stored in vast databases, and computer programs are used to analyse the data to find trends, patterns, similarities, correlations or causal relationships.

4 The human face of science

Collaboration and community

Science in the 21st century is very much a collaborative and global affair. The complexity of the problems we face – such as how to develop sustainable fusion energy, curing cancer, dealing with the greenhouse effect, the energy crisis – all require a collaborative and transdisciplinary approach. This approach can be successful because of the consistency in the training of scientists. A biochemist from Zambia would do her research in the same way as one who received his training in Australia.

Collaboration extends to scientists working with engineers and technologists. The complex problems mentioned above contain pure research questions as well as applied aspects. For the latter, technologists and engineers are needed to translate the pure research findings into practical applications. For example, a team trying to find a cure for melanoma (a type of skin cancer) may consist of biochemists, medical doctors, radiologists, molecular biologists, chemists, physicists, pharmacists and technicians.

Collaborative work can involve laboratories from a number of different universities, and from industry, hospitals and other institutions. This transdisciplinary, and often international, community enables teams to mount a concerted effort to tackle a problem from many angles and using a variety of approaches. It brings together people from different backgrounds and with different skill sets but with a common goal. This helps to ensure that the research programme as a whole is open-minded and unbiased: any prejudices that might exist within an individual scientist or team are counterbalanced by the presence of people with different points of view.

This approach increases the chances that a solution to a particular problem will be found. It is extremely rare these days that an individual scientist is capable of solving very complex problems. A collaborative approach also allows more efficient use of equipment: not all labs involved in a project need to purchase the same expensive tools. However, even though the sharing of equipment may bring down the overall costs, science remains extremely costly. Very large international projects are only possible because many nations collaborate and contribute funding.

Examples of international collaboration

In 2003, the first complete human genome was published by the **Human Genome Project (HGP)**. This was the result of 13 years of work coordinated by the US Department of Energy (<http://energy.gov/>) and the National Institutes of Health (<http://www.nih.gov/>). Other contributions to the project came from the Wellcome Trust (<http://www.wellcome.ac.uk/>), as well as groups in Japan, France, Germany and China. You can access the DNA sequence online: http://www.ornl.gov/sci/techresources/Human_Genome/home.shtml

This section covers:

- collaboration and community
- how scientists publish their work
- intellectual property
- science, ethics and the precautionary principle
- honesty in science: plagiarism and other forms of cheating
- funding and political influence.

The **Intergovernmental Panel on Climate Change (IPCC)** brings together more than 2500 scientists from around the world. It was established in 1988 to provide a clear scientific world view on the current state of knowledge about climate change and its potential environmental and socio-economic impacts.
<http://www.ipcc.ch>

The **Large Hadron Collider (LHC)** is the biggest man-made experiment in the world, housed at the CERN (the European Organization for Nuclear Research) laboratory in Geneva. Scientists of more than 100 nationalities based all over the world work together to interpret the results obtained from the LHC.
<http://home.web.cern.ch/>

An overview of scientific journals can be found here: <http://www.sciencedirect.com/science/journals>

Note that this list is by no means exhaustive.

How scientists publish their work

Scientists publish their results in scientific journals to make them available for other scientists to read and use. There are thousands of journals worldwide, both hard copy and online, where those findings may be published.

When scientists intend to publish in a scientific journal, the paper is subjected to **peer review**. This means that the paper is read and criticised anonymously by fellow scientists (peers). They will assess and check several aspects of the paper: whether the findings are novel enough for publication, whether the correct procedures have been followed, that there is no indication of plagiarism and that the report is properly referenced. In addition, they might look for conflict of interest or whether similar results have been published before. An example of a conflict of interest is when a paper demonstrates the efficiency of a new drug and the funding for the project comes from the company who produced that drug. In such cases, the results should be carefully checked for any sign that they are presented dishonestly. If all the required conditions are met, the reviewers will give the journal's editor the go-ahead for publication. Once published, the paper may be quoted by other researchers in the same field. If the findings are exceptional, they may also be quoted in the national press or on online news sites.

With the advent of online publications, an increasing number of journals are being made available for free, and a new form of peer review has emerged. Traditional journals use a team of in-house editors and trusted outside scientists to review a paper before it is accepted for publication by the journal. In the case of online publications, such as those published by the Public Library of Science (PLOS), all scientists (peers) are free to review and comment on the data. This is an open, transparent procedure rather than the closed approach used by journals. Publications are a quantifiable indication of the productivity of science.

Besides publishing in journals, scientists also present their findings at (international) conferences. These presentations usually communicate initial findings that have not yet been included in a full paper and are generally not peer reviewed, although some conferences will assess the quality of the presentations before accepting them.

PLOS

The Public Library of Science (PLOS) is a non-profit publisher [...] with a mission to accelerate progress in science and medicine by leading a transformation in research communication. (Source: <http://www.plos.org/>)

PLOS has gained quick recognition and is now a sought-after publication platform. It is freely available online.



Intellectual property

Scientists are employed by universities, institutes, hospitals and other organisations where they work in teams. Their employers often demand that they sign an agreement as part of their employment contract which gives all the intellectual rights to their discoveries to the organisation they work for. If a research finding has an applied aspect – for instance, if a new drug could be developed – it can be lucrative to apply for a **patent**.

Applying for a patent is expensive, but it is financially attractive because a patent grants the exclusive rights to use or sell the new discovery to a person or company for a period of up to 20 years. Often, all the monetary rewards go back to the company. In the case of some drugs, the financial gains for the (pharmaceutical) company can be enormous. It is estimated, for example, that the drug Tagamet (used in the treatment of stomach ulcers) earned SmithKline Beckman Corporation approximately US\$1 billion per year in the 1980s. The possibility of patenting a discovery helps make it attractive to companies to invest huge sums of money in developing new drugs.

A considerable downside to this practice is that a patent gives a pharmaceutical company a monopoly position for a particular type of drug. Within certain limits, the company can charge whatever it chooses. Of course, a company needs to recoup its costs – to get medical drugs approved for the market is a lengthy and expensive process – but, as a result, the newest drugs are expensive. This means that many people, such as those living in developing countries, are denied access to the latest medication.

Many thousands of patents are awarded worldwide every year. The European Patent Office (<http://www.epo.org/index.html>) has a searchable database.

Science, ethics and the precautionary principle

The field of **ethics** (or moral philosophy) deals with what is right and what is wrong. You may wonder how science can be right or wrong when it only tries to get to the truth. But to discover some truths it may be necessary to do things we consider morally wrong, which is not acceptable. For example, nobody would condone the use of human babies in medical experiments.

Scientists therefore have to be aware of the ethical implications of their work. In the first instance, they must consider the ethical aspects of their research design. To this end, governments and institutions have strict guidelines for scientific experiments involving humans or animals, and such research has to be approved by ethics committees.

But scientists must also consider the ethical aspects of the ways in which their work can be applied. Discussions on such subjects affect the wider public and they are frequently carried out in political and public forums. An example of an issue that raises widespread ethical questions is gene therapy. This technology involves changing a person's genetic make-up and has been accepted as a means of curing certain genetic diseases. However, one might ask whether it is acceptable to change a person's genes. And, if it is in some instances – for medical benefit – where should the line be drawn? Would it be acceptable to use gene therapy to 'improve' someone's behaviour or appearance, for example?

Science deals with all aspects of human life and it has the potential to solve many pressing problems. It is undeniable that science, with its partner technology, has been essential in bringing progress to many

areas, and this has led some scientists to proclaim that everything can be (re)solved by science. Many developments have undoubtedly been to humanity's advantage, but some inventions have the potential to be used for harmful purposes, for instance in warfare. The discovery and technological development of nuclear fission is a well-known example: it has led to the development of important nuclear power plants, but it has also led to nuclear weapons.

Scientists must therefore consider carefully whether their research could have long-ranging and far-reaching effects, in which case an in-depth discussion should precede further work in this area. Such discussions should involve policymakers as well as scientific experts, and they should include risk assessments and plans for how to manage the risks identified. If there is good reason to believe that a new technology may have harmful effects but the evidence is not clear, then the **precautionary principle** may be applied. This ensures that measures will be taken to protect the public from any risk until new evidence shows that the risk is of an acceptable level. For example, if there is good reason to believe that a particular pesticide is responsible for a reduction in bee populations – which is a very serious problem because bees pollinate many important crops – the precautionary principle states that that pesticide should be banned until the manufacturer can prove that it is not in fact harmful.

Honesty in science: plagiarism and other forms of cheating

Society expects those involved in searching for the truth to have integrity and honesty when it comes to publishing their results. There is an expectation that the data should be honestly represented, not manipulated to better fit the theory, and that any findings used to corroborate or support these data which are not the scientist's own should be properly referenced. There is considerable pressure on scientists to publish – it increases their chances of being promoted, getting more funding, and so forth – and, unfortunately, this pressure can lead to cheating.

Manipulation of data

Doctored data to make them better fit the theory or support a hypothesis is unfortunately not an uncommon occurrence. One well-documented example concerned Marc Hauser, an evolutionary biologist and professor at Harvard University. After students working in his lab reported that data in his papers were falsified, the university investigated Hauser's possible scientific misconduct. An external investigation confirmed the allegations and Hauser ultimately resigned from his post in 2011.

Falsifying data is totally unacceptable and it can have wide-ranging implications for the work of other scientists. Scientists' work is frequently based on earlier findings, and time and money are invested to repeat those findings or to corroborate them. If it is then revealed that the research was based on fraudulent data, a lot of work has been wasted. There may also be a risk of direct harm, for example if doctored data in medical research were to lead to an unsafe drug being tested on humans.



Plagiarism

Properly quoting other people and referencing work that is not the scientist's own are the norm in scientific publications. Not complying with this convention is a form of **plagiarism**. The advent of specialist computer software has made it relatively simple to assess if a text has been plagiarised. Any form of plagiarism is taken very seriously and there have been some widely publicised cases of plagiarism leading to the dismissal of the perpetrators.

Funding and political influence

Pure research is mostly funded by public institutions and governments. Research grants are available and scientists wishing to work on a particular topic have to submit research proposals which are vetted by peer review. It is a highly regulated and standardised process. Funding is limited and decisions regarding which proposals receive funding may be influenced by political considerations. Scientists therefore have to be able to make a strong case for why their research proposal is important.

Not all scientific research is conducted in publicly funded institutes, though. The defence industry and the pharmaceutical industry employ thousands of scientists who work in closed, protected conditions. The research conducted here is mostly applied research, with a fixed goal in mind. Although working for these organisations may have advantages, there are usually certain conditions imposed. Scientists are limited in what they can discuss, and publishing their findings is restricted or forbidden. The intellectual property rights or patents coming out of this research remain with the company or the defence department.

Advances in science and technology can have significant economic and political implications for a nation. For example, if research into the use of nuclear fusion energy shows that this type of energy is feasible in the very near future, it may impact on the levels of employment in oil and other energy-related industries. Politicians may not wish to see these findings published. They may have a number of valid reasons for this but it demonstrates that science can be influenced by politics.

The Lysenko affair (see right) is a good historical example of how politics may influence scientific ideas. The debate around climate change is a current, highly politicised issue. Scientists themselves find it hard to reach a consensus on how climate change will develop, how it will affect us and at what rate. The debate in science is based on the interpretation and extrapolation of data and not on personal feelings. Decisions by politicians may be influenced by the length of their terms in office or the strength of a lobbying group. However, a policy to deal with the effects of climate change, by the very nature of the problem, must be long term and demands international collaboration. Such policy decisions should ideally be based on science alone, though in practice this is hard to achieve.

The Lysenko affair

Trofim Lysenko (1898–1976) was a Soviet biologist and agronomist of Ukrainian origin who rejected Mendelian genetics. He believed that characteristics acquired by an organism during the course of its life would be passed on to the next generation and he made suggestions for improving the growing of crops based on this theory.

In the 1930s and 1940s, Joseph Stalin's forced collectivisation of the agricultural sector in the Soviet Union (USSR) caused massive production loss and resulted in famine. The country could no longer feed its own population. Lysenko's research into crop improvements was supported by the Soviet leadership and earned him the post of Director of the Institute of Genetics within the USSR's Academy of Sciences. This position allowed him to exercise political influence and power to entrench his anti-Mendelian doctrines further in Soviet science and education. Ultimately, Lysenko's theories were outlawed in 1948.

This section covers:

- science and the public
- fallacies
- pseudoscience.

Examples of scientific topics that have been the subject of public debate include:

- genetically modified foods
- nuclear energy
- climate change.

5 Public understanding of science

Science and the public

Science is inextricably linked with our lives. Communication, transport, the internet, what we eat, medicine – each and every aspect of our lives is influenced by science. It is therefore helpful if members of the public have a basic understanding of the nature of science. With that, they can make informed decisions for themselves and contribute constructively to public debate on matters related to science.

You may like to research one of the topics listed here, to find out how non-scientists have contributed to the debate.

- What kind of understanding do you think non-scientists need in order to develop an informed opinion on scientific topics?
- How have these debates been shaped by people who may not have a good understanding of the issues?

Communication between scientists and the public may be complicated by the use of scientific terminology as well as by different interpretations of certain terms. For instance, as we have seen, the public and scientific understanding of the word ‘theory’ are different: contrary to the general understanding of it being just something that might be possible, in science it denotes a model or set of laws which can be used to make predictions. The theory of fluid dynamics, developed by Swiss mathematician Daniel Bernoulli (1700–1782), plays an essential role in the development of aeroplane wings. If it were just a ‘theory’ in the lay public’s understanding of the word, it is highly unlikely that many people would ever board an aeroplane. So, explaining the terminology and its context is a good starting point for clear communication.

Another area that often causes confusion is statistics, mathematics and risk. This is partly due to some people not having a good understanding of these subjects and partly because the media frequently present results in a dramatic and sensational way, to grab readers’ attention. For example, a headline could state that drinking fizzy drinks increases the risk of pancreatic cancer by 90%. This sounds extremely serious. However, in practice, it may mean that the lifetime risk of developing pancreatic cancer increases from, say, 1.5% to 2.9%. This would still be significant, but it does not mean that drinking fizzy drinks will almost definitely give you cancer, as some people may think from reading the headline. Moreover, this result may be based on a single study that has not yet been replicated. It is therefore vital that scientists do what they can to present results in such a way that the public can understand the real risks involved. It is also important that the public have a good enough understanding of these subjects to be able to interpret the real implications of reported studies.

The idea of knowing something for certain can also be problematic. Statistics can give us a certain level of confidence in our results but it is rarely possible to know something with 100% certainty. In fields such as biology and medicine, there are many exceptions to rules. A scientist would therefore be lying if they stated that something will always be the case, that the outcome is a dead certainty. However, the public often want a definite answer.



Fallacies

A **fallacy** is a misleading or false argument, something that does not logically support the case a person is making. Both scientists and the public need to be aware of common fallacies, so that they can recognise them in scientific debate and avoid using them themselves. Common causes of these flaws in logic are an ignorance of scientific methodology and unstructured critical thinking.

The following are the most common forms of fallacy.

- **Confirmation bias** has already been introduced. In public debates about science, confirmation bias can affect whether members of the public accept a scientific message. For example, someone who believes in acupuncture is unlikely to accept a report that states that acupuncture does not have any medicinal effect.
- **Hasty generalisations** occur when people base a broad conclusion or theory on just a few observations. This is essentially an extreme form of inductive reasoning. A particularly harmful hasty generalisation in the public understanding of science is to conclude that all science must be untrustworthy because some theories in the past have turned out not to be true.
- Related to hasty generalisation is the use of **anecdotal evidence** based on subjective 'evidence' or 'hearsay'. An example would be along the lines of 'My father smoked until he was 90 and he never had lung cancer' as an argument against the established causal link between smoking and lung cancer.
- The **post hoc ergo propter hoc fallacy** assumes that, if an occurrence A is seemingly directly followed by an event B, B must be caused by A. An example might be if a mobile phone mast was erected in an area and a few people in that area subsequently get cancer. The fallacy may lead people to conclude that the mast caused the cancer, but it is possible that it is just a coincidence. This is a very common fallacy and relates directly to the correlation versus causation debate.
- In the **straw man fallacy**, side A in a debate distorts or misrepresents the argument put forward by side B and attacks the distorted argument rather than side B's actual argument. By doing this, side A avoids addressing the real issue. A commonly seen straw man argument is that the theory of evolution is not a valid theory because it does not give a satisfactory explanation for the origin of life. This is a straw man because the theory of evolution does not claim to explain the origin of life – the theory is about what happened to life after it began.
- **Redefining** is to attach a new definition to a term or concept in the middle of a discussion. This is best explained by an example. Person A states: 'Either it is a living organism with DNA as the genetic material or it is a virus.' Person B replies: 'Everything is alive; we do not know everything about viruses.' This is redefining the central idea in person A's statement, which is that all living organisms have DNA as their genetic material. Person B is therefore not really addressing the essence of A's argument.

The use of these types of fallacy is widespread. Note, however, that use of a fallacy does not necessarily make an argument wrong; it just makes it logically invalid. Using fallacies or ignoring established scientific methodologies will result in 'pseudoscience'.

Pseudoscience

As the name implies, **pseudoscience** is a false form of science (*pseudo* is Greek for ‘false’). Pseudoscience results when biases and fallacies are not avoided, or when the standards of scientific methodology are not adhered to. Homeopathy and acupuncture are examples of pseudoscientific practices that have been shown to have no effect when tested under strict scientific conditions. Intelligent design is a theory that is considered pseudoscientific because it is not testable or falsifiable.

Pseudoscientists sometimes claim that their theories are based on evidence obtained using scientific methodologies. However, closer observations make it clear that their findings cannot be repeated under controlled conditions. Proponents of pseudoscience disqualify this with fallacious arguments, such as ‘the conditions were not exactly the same’, ‘you were cheating’ or ‘I have proof that it does work’. Resisting and rejecting any evidence that challenges its theories distinguishes pseudoscience from true science: scientific theories are constantly tested and adapted if they prove to be wrong. Science is based on evidence, pseudoscience is based on beliefs.

Benveniste’s famous claims about the memory of water as evidence for homeopathy make it clear that even trained scientists can make mistakes that lead to pseudoscience.

The ‘memory of water’ experiment

Jacques Benveniste (1935–2004) was a French immunologist who was at the centre of a major international controversy in 1988, when he published a paper in the scientific journal *Nature*. It described the action of very high dilutions of an antibody on human white blood cells and his findings seemed to support the principle of homeopathy.

Homeopathy is based on the premise that ‘a substance that causes the symptoms of a disease in healthy people will cure similar symptoms in sick people’. In 1796, this form of alternative medicine was first proposed by Samuel Hahnemann (1755–1843). Preparing homeopathic medicines uses repetitive dilutions of a dissolved substance. Dilution factors of 1 in 10^{24} are purported to be effective. At these high dilutions, effectively none of the original (dissolved) substance can be found in solution.

Benveniste used this approach to test if antibodies could still trigger a reaction in human white blood cells. According to the original publication, these very high dilutions still caused an effect. The effect was referred to as the ‘memory of water’.

The claims were highly controversial and, as a condition of publication, *Nature* asked for the results to be replicated by independent laboratories. After the article was published, a follow-up investigation was carried out with the cooperation of Benveniste’s own team. It failed to replicate the original results. Subsequent investigations by other research teams also could not corroborate the original claims. Benveniste refused to retract his controversial article. He claimed that the follow-up investigation had deviated from the original protocols and therefore that these new findings were invalid.



Final note

Science is one of humanity's greatest creations. Its achievements touch every aspect of life and have brought progress to many millions of people. These achievements are the result of collaboration, adherence to strict protocols, persistence, corroboration or falsification of previous findings, and a deep trust of the principles of science.

Many big questions are still unanswered. A large number of the problems we are facing are intercultural or international in scope and epic in size – just think of climate change, the energy crisis, curing cancer, or the rapid evolution of bacteria and viruses. Improving our chances of success requires international coordination and substantial funding, but all these challenges can be conquered.