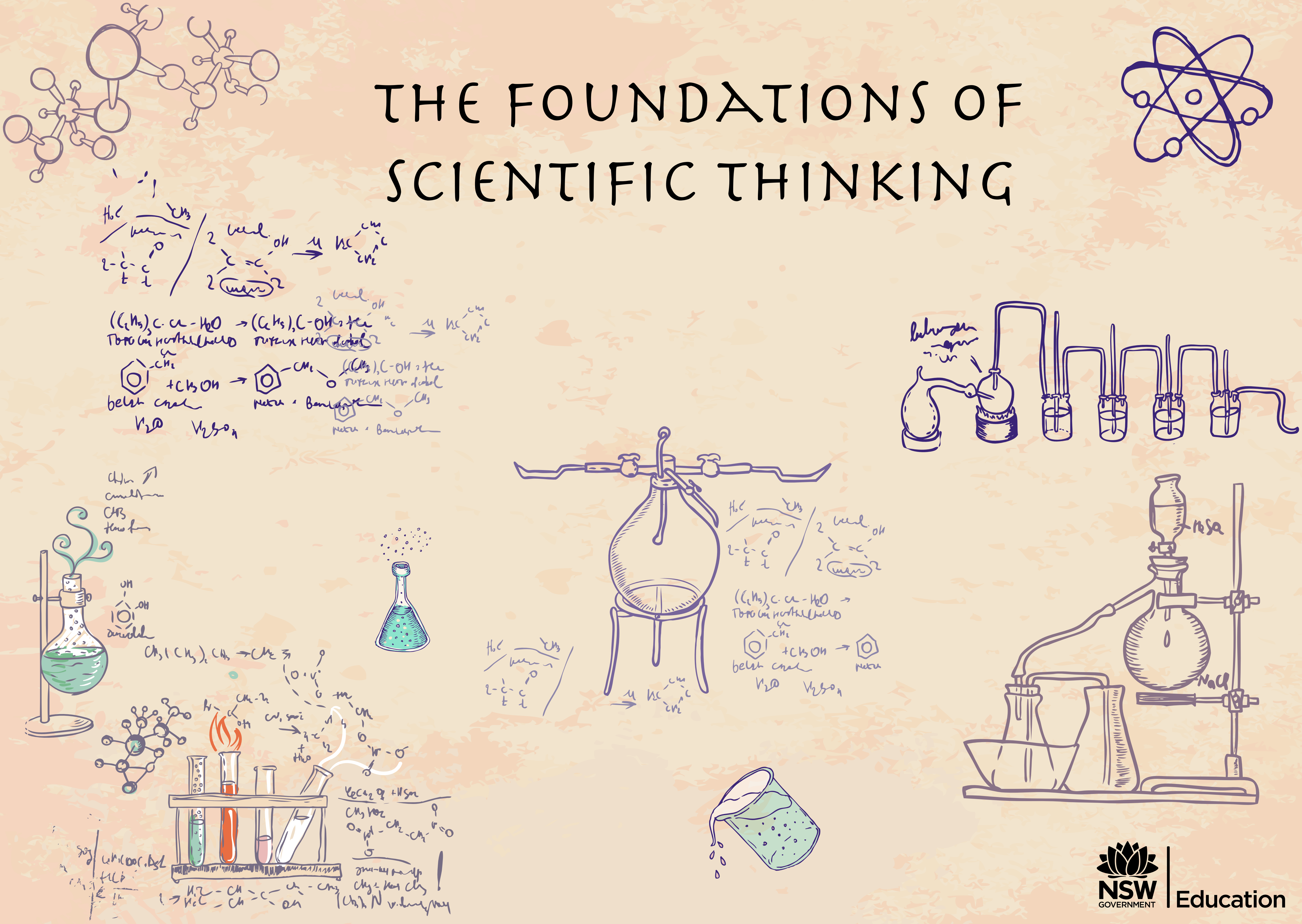
THE FOUNDATIONS OF SCIENTIFIC THINKING



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Preface

The new stage 6 science syllabuses implemented in 2018 are centred on inquiry-based learning pedagogies. Inquiry sits at the heart of the scientific process and the methods of inquiry are influenced by historical, philosophical, and cultural factors. These factors also affect science teaching and learning. It is well-established that science is not merely a collection of concepts and should not be taught in that vein in classrooms. Thus, in addition to science experiments and laboratory practicals, students in most stage 6 science courses must participate in inquiry-based depth studies. In the investigating science and science extension syllabuses, students explore the nature and practice of science, including the historical and philosophical factors that influence scientific thinking. For example, all high school science students must know the importance of constructing hypotheses when conducting investigations. However, hypothesis-based inquiries have a long philosophical history – falsifiability, deductive reasoning, empiricism and *a posteriori* philosophies! This document introduces some of these ideas, which form the basis of concepts discussed in Module 1 of the science extension syllabus, as well as in the investigating science syllabus.

> 'I fully agree with you about the significance and educational value of methodology as well as history and philosophy of science. So many people today - and even professional scientists - seem to me like somebody who has seen thousands of trees but has never seen a forest. A knowledge of the historic and philosophical background gives that kind of independence from prejudices of his generation from which most scientists are suffering. This independence created by philosophical insight is - in my opinion - the mark of distinction between a mere artisan or specialist and a real seeker after truth.'

Albert Einstein, in a correspondence to Robert Thorton, 1944

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Syllabus links

This resource provides information for instruction in the Stage 6 Science Extension and the Investigating Science courses. It may be used to address the following syllabus outcomes:

Science Extension

Module 1 The Foundations of Scientific thinking

- Content: The Development of Modern Science
    - Inquiry question: How have philosophical arguments influenced the development of modern scientific research?

Investigating Science

Module 1 Cause and Effect – Observing

- Content: Role of Observations
    - Inquiry question: How does observation instigate scientific investigation?
- Content: Observations
    - Inquiry question: What are the benefits and drawbacks of qualitative and quantitative observations?
- Content: Observations as Evidence
    - Inquiry question: How does primary data provide evidence for further investigation?
- Content: Observing, Collecting and Recording Data
    - Inquiry question: How does the collection and presentation of primary data affect the outcome of a scientific investigation?
- Content: Conclusions Promote Further Observations
    - Inquiry question: How do conclusions drawn from the interpretation of primary data promote further scientific investigation?

Module 2: Cause and Effect – Inferences and Generalisations

- Content: Observations and Inferences
    - Inquiry question: What inferences can be drawn from observations?
- Content: Observing Patterns
    - Inquiry question: How does humans' ability to recognise patterns affect the way they interpret data?
- Content: Developing Inquiry Questions
    - Inquiry question: How can hypotheses and assumptions be tested?
- Content: Generalisations in Science
    - Inquiry question: What generalisations and assumptions are made from observed data?
- Content: Peer Review
    - Inquiry question: What role do peers play in scientific investigation?

Module 3: Scientific Models

- Content: Constructing a Model
    - Inquiry question: How can a model be constructed to simplify understanding of a scientific concept?

Module 4: Theories and Laws

- Content: Introduction to Scientific Theories and Laws
    - Inquiry question: What are the differences and similarities between scientific theories and laws?
- Content: Development of a Theory
    - Inquiry question: What leads to a theory being developed?
- Content: Development of Laws
    - Inquiry question: What leads to the acceptance of a scientific law?

Module 5: Scientific Investigations

- Content: Different Types of Scientific Investigations
    - Inquiry question: What type of methodology best suits a scientific investigation?

Module 7: Fact or Fallacy?

- Content: Impacts on Investigations
    - Inquiry question: What factors can affect the way data can be interpreted, analysed and understood?
- Content: Evidence-based Analysis
    - Inquiry question: What type of evidence is needed to draw valid conclusions?
- Content: Reading Between the Lines
    - Inquiry question: How does the reporting of science influence the general public's understanding of the subject?
- Content: Science as Self-correcting – the Issues
    - Inquiry question: Can the scientific community and process of peer review find 'the truth'?

Introduction to the nature of science

What is science? Unfortunately, that is not a simple question to answer. Most people agree that science is

- The set of systematic processes that allow us to understand ourselves and the universe that we inhabit, and
- A body of knowledge developed through the scientific process.

In other words, science is more than a collection of facts. Scientific knowledge has specific characteristics which define how it is generated and how it is used. Students must not only understand science concepts, but also the nature of scientific knowledge. However, most classroom instruction focusses on scientific outputs (theories, models and laws), rather than the processes involved in generating them.

> "Science presumes that the things and events in the universe occur in consistent patterns that are comprehensible through careful, systematic study. Scientists believe that through the use of the intellect, and with the aid of instruments that extend the senses, people can discover patterns in all of nature ... Science also assumes that the universe is, as its name implies, a vast single system in which the basic rules are everywhere the same"[1].

The paradigms of modern science are deeply rooted in ancient histories and philosophies. Indeed, before the early 19th century, science was referred to as 'natural philosophy'. It was only in 1834 that the British historian and philosopher, William Whewall, first used the word 'science' (derived from the Latin '*Scientia*', meaning 'knowledge') to describe the work of people who strove to understand natural phenomena. Cultural constructs influenced scientific practices. Modern science is largely the product of Western cultural thought. Cultural constructs have also influenced the way knowledge is acquired in other societies, such as Chinese, Indian, Middle Eastern and Australian Aboriginal societies. By comparing knowledge acquisition in these societies with those of Western societies, we can gain insights into how scientific practices differ in different parts of the world.

The scientific process

All scientific investigations begin with an inquiry question. The purpose of the investigation is to collect observations and other data to answer the inquiry question. It is the process of science that distinguishes science from other inquiry approaches, such as religion and philosophy. Scientists use observations in one of two ways:

- To develop new theories to explain some natural phenomena.
- To verify theories through hypothesis testing.

Observations lead to inferences, and inferences are used to develop conclusions. For example, when studying populations of organisms, Charles Darwin made two observations:

- Observation 1: members of a population often vary in their inherited traits.
- Observation 2: all species can produce more offspring than the environment can support, and many of these offspring do not survive and reproduce.

From these observations, he developed two inferences

- Inference 1: Individuals whose inherited traits give them a higher probability of surviving and reproducing in a given environment tend to leave more offspring than other individuals.
- Inference 2: This unequal ability of individuals to survive and reproduce will lead to the accumulation of favourable traits in the population over generations

From these inferences, Darwin concluded that populations evolve through the process of natural selection. This conclusion, together with other evidence, led to the development of the Theory of Evolution by Natural Selection. This theory was able to explain

- The unity of life
- The diversity of life
- The adaptation of organisms to their environment

Teaching the nature of science

Einstein (1933)[2] said that if we wanted to know how scientists carry out their work, then we should not listen to them, but watch how they ply their trade. Driver *et al*., (1996)[3] said that students learn about the nature of science because it allows them

- To make sense of the scientific objects and processes that people encounter in their daily lives.
- To make sense of socio-scientific issues and participate in the decision-making process.
- To appreciate science as a major element of contemporary culture.
- To understand the norms of the scientific community.

Importantly, Driver *et al* (1996) maintain that teaching the nature of science supports the successful learning of science content. Students should understand that the scientific realm is seething with ideas, which are subject to the selective forces of experimentation, observation and hypothesis testing. Through these processes, robust ideas that are supported with rigorous evidence replace ideas that are weak or unsubstantiated. Thus, scientific knowledge is not static, but dynamic. This inevitable evolution of concepts deepens scientific understanding. When science is seen as a process that improves our understanding of the natural world, it is apparent the 'tentativeness' of scientific knowledge is its strength, rather than its weakness.

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[1] Rutherford, F.J. and Ahlgren, A., 1991. Science for all Americans. Oxford university press.

[2] Einstein, A., 1934. On the method of theoretical physics. Philosophy of science, 1(2), pp.163-169.

[3] Driver, R., Leach, J. and Millar, R., 1996. Young people's images of science. McGraw-Hill Education (UK).

Thomas Kuhn, in The Structure of Scientific Revolutions (1970)[4], makes clear that science textbooks convey an image of what science is and how it works. He wrote that

> 'More than any other single aspect of science, the textbook has determined our image of the nature of science and of the role of discovery and invention in its advance'.

In other words, textbooks often depict the nature of science incorrectly. Often, those depictions may have a lasting influence on students' understanding of science.

Myths about the nature of science

Numerous studies have shown that misconceptions about the nature of science persist in our societies. Some of them have become so ingrained that they are difficult to eliminate, even in the face of contrary evidence. Here is a list of some common misconceptions about the nature of science, which are described in detail in the following section:

- Hypotheses become theories that, in turn, become laws.
- Scientific laws and theories are absolute.
- A hypothesis is an educated guess.
- A general and universal scientific method exists.
- Evidence accumulated carefully will result in certain knowledge.
- Science and its methods provide absolute proof.
- Science is more procedural than creative.
- Science and its methods can answer all questions.
- Scientists are objective.
- Experiments are the principal route to scientific knowledge.
- Scientific conclusions are reviewed for accuracy.
- Acceptance of new scientific knowledge is straightforward.
- Science models represent reality.
- Science is a solitary pursuit.

Hypotheses become theories that, in turn, become laws

This myth is based on the erroneous notion that hypotheses eventually mature into laws. It assumes that hypotheses and theories are flimsy conjectures, while scientific laws are robust and authoritative conclusions. This notion also assumes that, as more evidence and data accumulate, theories and hypotheses will transform into scientific laws. These ideas are false. Scientific laws are **descriptions** (for example - generalisations, principles or patterns) of natural phenomena and theories are the **explanations** of those generalisations. For example, in chemistry, Boyle's Law describes the relationship between the pressure and the volume occupied by a gas. It is represented mathematically as $PV=K$

Where,

P = pressure
V = volume
k = a constant (that is characteristic of a particular gas)

Although Boyle's Law **describes** the relationship between gas pressure and volume, it does not **explain** why that relationship occurs. Indeed, to explain Boyle's Law, we must rely on the Kinetic Theory of Gases and the Atomic Theory. When discussing his Law of Gravitation, Sir Isaac Newton wrote (in his book, Principia)

> 'I have not been able to discover the cause of those properties of gravity from phenomena, and I frame no hypothesis … it is enough that gravity does really exist, and act according to the laws which we have explained'[5].

Hypotheses, theories and laws are equally valid, but only differ in their scope.

Scientific laws and theories are absolute

Scientific knowledge is not rigid and absolute, but is tentative in nature. The tentative nature does not mean that the knowledge is not valid but illustrates its dynamic nature. It also highlights the self-correcting nature of science. Scientific laws are subject to change and modification. For example, while Newton described gravitation as a force between two masses, Einstein said that gravitation is the result of the curvature of space-time. **Despite its dynamic nature, scientific knowledge is durable.**

A hypothesis is an educated guess

Describing scientific hypotheses as 'educated guesses' has resulted in an unfortunate consequence – many people consider hypotheses to be conjectures. Scientific hypotheses are not guesses or conjectures. Hypotheses are an important tool used to verify scientific information. They are based a considerable body of scientific knowledge and understanding. **A better description of hypotheses is that they are tentative explanations for some natural phenomena**. They are predictive statements that are based on contemporary scientific concepts and form the basis of experimentation or other scientific endeavours.

A general and universal scientific method exists

One commonly-held belief in the general community is that science operates via an invariant set of processes called the scientific method. This notion came about because of efforts in the 20th century to define the characteristics of scientific research. As a result, an ordered list of steps depicting the scientific process was produced. Science textbooks adopted this list as the scientific method and that idea has since prevailed. However, the steps of the scientific method are used to communicate research findings, rather than representing the research process itself. Indeed, research processes are highly varied and there is no universal methodology that all scientists use.

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[4] Kuhn, T.S., 1970. The structure of scientific revolutions, International Encyclopaedia of Unified Science, vol. 2, no. 2. p143

[5] Shapiro, A.E., 2004. Newton's" experimental philosophy". Early Science and Medicine, 9(3), pp.185-217.

- Define the problem
- Gather information
- Form a hypothesis
- Make relevant observations
- Test the hypothesis
- Form conclusions
- Report results

So pervasive is this misconception that the Nobel laureate, Peter Medawar, called the scientific paper a fraud, since it rarely reflects how the problem was investigated.

Evidence accumulated carefully will result in sure knowledge

This statement oversimplifies the processes used to construct scientific knowledge. The statement represents only one part of the scientific process. The approach of generating theory from evidence/data is called induction. However, a related but complementary process, called hypothetico-deduction (or simply deduction), verifies the theories produced by induction. For example, after examining numerous plant and animal specimens under the microscope, the German scientists, Schleiden and Schwann, generalised that all living things are composed of basic building blocks called cells. This process is an example of inductive thinking. Together with other findings, the generalisation came to be called the cell theory. Deductive thinking on the other hand, develops several hypotheses from the cell theory, which are then tested in experiments. Together, both induction and deduction reasoning add to scientific knowledge. No matter how scientific knowledge is developed, a lot of evidence goes into its construction. However, **all scientific knowledge is durable, but is tentative**. This feature of scientific knowledge highlights its dynamic nature.

Science and its methods provide absolute proof

Science does not espouse ideas such as absolute truth. Instead, science purports that we get a truer picture of reality by eliminating what is false. Thus, through experimentation and observations, scientific processes disprove that which is false. It is important to remember that **hypotheses cannot be proven, but only disproven**. By disproving hypotheses, we discard false ideas about a theory. This process strengthens theories. For example, if we have observed only white swans, we may generalise that 'all swans are white' (this is an example of induction). Sighting even a single black swan disproves this theory, or least requires us to modify the theory – 'most swans are white'. Such self-correcting processes (for example - tentative nature of scientific knowledge) are inherent in science and is the reason why scientific thinking is powerful.

Science is more procedural than creative

This statement is another misconception of the scientific method. If the scientific method was true, then it follows that the scientific process must be procedural (i.e. the scientific process is nothing more than a step-by-step approach to an inquiry (methodological)). As discussed above, there is no 'standard' scientific method that all scientists follow. If science is procedural, then all scientists studying a phenomenon will arrive at the same conclusion. However, the history of science is replete with examples wherein scientists exploring same phenomenon arrive at different conclusions. For example, Newton concluded that the mass of an object is a fixed property (inertial mass), while Einstein showed that under certain conditions, the mass of an object might change (relativistic mass). Similarly, while studying combustion, Joseph Priestly explained the process using the phlogiston theory (even though he had isolated oxygen), while Lavoisier described combustion in terms of the reactions of substances with oxygen. These examples demonstrate the creative nature of making and analysing scientific observations.

Science and its methods can answer all questions

There are limits to what science can investigate. Science explores natural phenomena but cannot investigate paranormal and supernatural events. These limitations are largely due to a characteristic of science known as **falsifiability**. Falsifiability refers to the fact that ideas should be testable via observations or experiments. If an idea is falsifiable, then it is scientific (for example - may be evaluated by scientific processes). Many areas of human inquiry are 'non-scientific' when viewed through this lens. For instance, religious beliefs are non-scientific because they cannot be falsified and validated through the hypothetico-deductive process. Science also cannot investigate questions in ethics, morality, aesthetics, philosophy and metaphysics.

Scientists are objective

Objectivity is an important aspect of scientific practice. However, objectivity is often difficult to attain, for the following reasons:

- While falsifiability is an attempt to enhance objectivity, not all scientists employ falsifiability (or deductive approaches) in their research.
- Confirmation bias and theory dependent observations are another reason for the lack of objectivity. Most scientists subconsciously hold on to certain preconceptions about the way the world works. These preconceptions may influence or bias the way scientists collect and interpret evidence. For example, a scientist may consider a piece of evidence to be irrelevant to his/her research and may exclude it from the ensuing publication. However, other scientists may consider the omitted evidence to be important. Such judgement calls are the result of theory-dependent observation.
- Objectivity may also be lost when scientists have expectations of the outcomes of investigations. For example, if a scientist were to obtain a result that is very different to some expected outcome, the scientist would often conclude that the unexpected result occurred because of some mistake in the methodology.

While a researcher may not be objective in his or her investigation, **the peer-review process and collaborative nature of science maximise objectivity**. Independent verification of data analyses and scientific conclusions imparts objectivity to a scientific enterprise.

Experiments are the principal route to scientific knowledge

Although experiments are central to the scientific process, they are not the sole means of acquiring scientific knowledge. Indeed, many of our most significant leaps in scientific understandings have not come from experimental science. The development of heliocentrism by Copernicus and Kepler, Darwin's Theory of Evolution by Natural Selection and Einstein's Theories of Relativity were all the products of detailed observations, or from the extensions and elaborations of contemporary ideas in science.

Scientific conclusions are reviewed for accuracy

This statement is, by-and-large, true, Science relies on the **peer-review process** to ensure the accuracy and authenticity of research. Before manuscripts are published, they are peer-reviewed by other scientists. The same process applies when scientists submit research proposals for funding. This review process is blind – the identity of the reviewers will not be revealed to the authors. However, sometimes, scientists choose to by-pass this rigorous peer-review process and publicise their work on non-peer-reviewed platforms, such as TV, websites, newspapers and magazines. In some cases, this has led to disastrous outcomes, as was the announcement of the discovery of cold fusion.

Acceptance of new scientific knowledge is straightforward

It is very difficult for new ideas to be accepted by the scientific community. **Professional skepticism** is a trait that is characteristic of science. For new ideas to be accepted, those ideas must be scrutinised for errors, as well as their ability to explain observations that contemporary ideas cannot. Many theories that are mainstream today took a long time to become established in the scientific community. Some examples of such ideas include the sun-centred solar system, the germ-theory of disease, evolution by natural selection and continental drift. While scientists construct knowledge of natural phenomena, scientists also set the standards by which new information is incorporated as scientific knowledge.

Scientific models represent reality

Since science works by constructing models and theories, it is often assumed that those models and theories are 'real'. However, one school of thought, known as **instrumentalism**, suggests that this is not so. Laws and theories are instruments for understanding reality but are not real in themselves. The opposing view of science, called **realism**, claims that laws and theories are indeed representations of reality. Instrumentalists claim that since scientific knowledge is tentative and subject to modification, they cannot be real and are only as useful as their capacity to explain natural phenomena. Consider the development of the atomic theory. From the works of the Greek philosophers to the contemporary Standard Model of the atom, our understanding of atomic structure has undergone significant change. Although no one has seen an atom, the standard model explains many aspects of the structure and function of matter (for example - from chemical bonding to gas laws). This model explains many observations about the structure and properties of matter. However, until today, atoms are invisible.

Science is a solitary pursuit

Scientific knowledge is rarely the product of a single mind. Even the great discoveries made by seemingly solitary scientists (e.g. Newton, Einstein, etc.) are the result of extensive collaboration and/or communication with other scientists. Einstein consulted many physicists and mathematicians when developing his ideas of Brownian motion, the photoelectric effect and relativity. Darwin, who was renowned at being reclusive, communicated extensively with other scientists[6], including Alfred Russell Wallace, who co-developed the idea of speciation resulting from natural selection. Modern science involves collaborations and negotiations between scientists, often on an international scale. Although individuals who possess keen insights or exceptional talent often appear to be solitary luminaries, most scientific endeavours require complex teams. For example, the sequencing of the genome of an organism requires teams of biologists, bioinformaticians and technicians to make sense of enormous quantities of data. The CERN experiment to determine the existence of the Higgs Boson at the Large Hadron Collider included about 5000 scientists!

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[6] Darwin Correspondence Project.

Epistemology

The word ‘epistemology’ refers to the nature of knowledge. It is formally defined as ‘a branch of philosophy that investigates the origin, nature, methods, and limits of human knowledge’. The term is derived from the Greek words, *epistēmē* (‘knowledge’) and *logia* (‘study of’). Scientific epistemology explores the nature of scientific knowledge. It consists of three aspects[7]:

1. The qualities of scientific knowledge
   a. Science attempts to explain natural phenomena.
   b. Scientific knowledge is represented as laws and theories. Laws and theories serve distinct roles in science – laws describe patterns and relationships in scientific information, while theories provide explanations of natural phenomena.
   c. Scientific knowledge, while durable, has a tentative character (subject to revision).
   d. People from all cultures contribute to science, as science is part of the social and cultural traditions of many human societies.
   e. Scientific ideas are affected by the social and historical setting.
2. The limitations of scientific knowledge
   a. Science does not make moral judgments (for example - should euthanasia be permitted?)
   b. Science does not make aesthetic judgments (for example - is Mozart’s music more beautiful than Bach’s?)
   c. Science does not prescribe how to use scientific knowledge (for example - should genetic engineering be used to develop disease-resistant crops?).
   d. Science does not explore supernatural and paranormal phenomena (for example, religious ideas and ghosts.)
3. How scientific knowledge is generated
   a. The development of scientific knowledge relies on observations, experimental evidence, rational arguments and skepticism.
   b. Scientific knowledge advances through slow, incremental steps (evolutionary progression), as well as through giant leaps of understanding (revolutionary progression) (see Kuhn’s discussion on paradigm shifts).
   c. Observations are theory dependent, which influences how scientists obtain and interpret evidence (see Popper’s discussion of falsifiability).
   d. There is no universal step-by-step scientific method. Scientific knowledge is acquired through a variety of different methods. Two main lines of reasoning that influence modern science are inductive (generalisations) and deductive processes (deriving).

> ‘Science distinguishes itself from other ways of knowing and from other bodies of knowledge through the use of empirical standards, logical arguments, and scepticism, as scientists strive for certainty of their proposed explanation’[8].

Web resource: The pursuit of ignorance (TED talk on the workings of science)

Web resource: What exactly is the scientific method?

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[7] Adapted from Understanding Science, accessed 10 September 2018

[8] National Research Council, 1996. National science education standards. National Academies Press.

Empiricism

The term empiricism is derived from the Greek word ‘*empeiria*’, which means experience. Empiricism is the theory that all knowledge is based on experiences derived from the senses. It purports that all rationally acceptable beliefs or propositions are knowable only through experience. Thus, empiricists claim that the mind constructs understanding and knowledge through experience, and not from innate ideas.

The philosophy of empiricism

Philosophically, empiricism is based on the principle of *a posteriori*. According to this principle, knowledge and concepts are derived from prior evidence[9]. For example, the statement ‘it is raining now’ is an *a posteriori* statement, as it is based on the **observation (evidence)** that rain is falling. So are statements such as ‘I passed my driving test’, ‘Water is made up of hydrogen and oxygen’ and ‘Infection by the influenza virus causes fever’. All of these statements are supported by prior information.

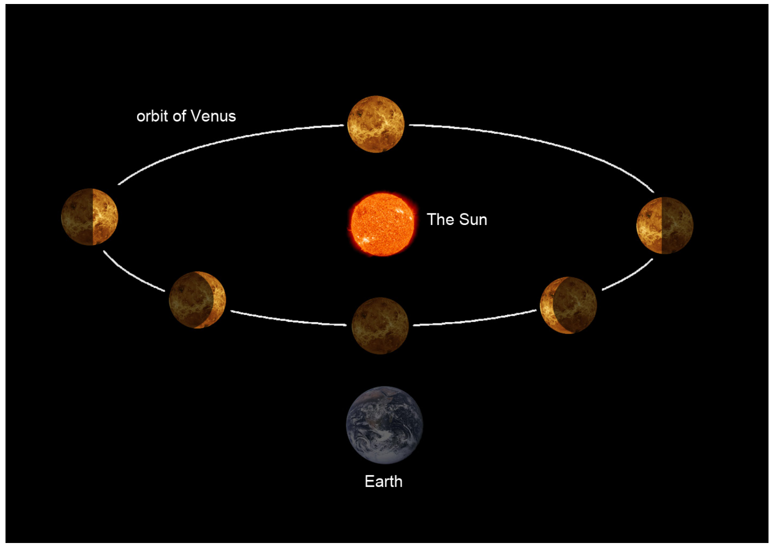
An example of empiricism in science

Galileo Galilei set science apart from philosophy through observation and experiment. In his book, The Assayer, he wrote

> ‘If experiments are performed thousands of times at all seasons and in every place without once producing the effects mentioned by your philosophers, poets, and historians, this will mean nothing, and we must believe their words rather than our own eyes?[10]’

Galileo disputed Aristotle’s and Ptolemy’s geocentric model of the solar system. Galileo trained his telescope on heavenly bodies and systematically collected data on the moons and planets of the solar system. Galileo noticed that Jupiter’s moons circled (orbited) the planet. This contradicted the geocentric model of the solar system, where the planets, moons and stars orbited a fixed Earth. Later, Galileo observed the phases of Venus, much like the phases of our Moon. Aristotle had rejected the heliocentric model because Venus’s brightness was always the same (according to Aristotle, Venus would be fainter when it was on the far side of the Sun relative to the Earth, and brighter when it was on the near side). However, he did not know about the phases of Venus. Since these phases can only be explained by Venus’ orbit around the sun, Galileo concluded that Venus and all the other planets must orbit the sun[11], just as the moon of Jupiter orbited the planet. Galileo surmised that Copernicus’ heliocentric model, where the sun is the centre of the solar system, is correct.

Empiricism and *a posteriori* are the bases for a reasoning tool in science, known as induction.



This figure shows the phases of the moon as viewed from the Earth[12]. Galileo explained that the phases of Venus were caused by its orbit of the sun. Geocentric models cannot explain this observation.

Web resource: Listen to a lecture on the quantitative methods in science (University of Amsterdam)

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[9] Internet Encyclopaedia of Philosophy

[10] Famous Scientists

[11] Galileo’s Observations of the Moon, Jupiter, Venus and the Sun

[12] Phases of Venus,

Rationalism

Rationalism is the theory that reason, rather than experience, is the foundation of knowledge. In other words, knowledge can only be constructed from reasoning and intuition. Rationalism is the opposing school of thought to empiricism.

The philosophy of rationalism

Rationalism is based on the principle of *a priori* reasoning. *A priori* means 'from the earlier'. It refers to the method of reasoning wherein conclusions are reached before evidence is obtained for those conclusions. Reasoning and logical thought are the foundations of *a priori* principle. For example, the following propositions are *a priori* statements:

- All bachelors are unmarried
- Cubes have six sides
- Today is Tuesday
- Red is a colour
- Seven plus five equals twelve

Each of these propositions is developed from definitions, rather than from observations.

Historical examples of rationalism in science

Thought experiments are typical examples of rationalism in science. In thought experiments, scientists develop their ideas from first principles, without conducting physical experiments. They rely on logic, rational reasoning, a vivid imagination, and a deep understanding of established principles to derive scientific explanations. For example, Galileo disproved the Aristotelian view that heavy objects fall to the Earth more quickly than lighter objects with a thought experiment[13]. In his book, 'Discourse concerning two new sciences', Galileo wrote

> 'If one were to remove entirely the resistance of the medium, all materials would descend with equal speed'.

Galileo's use of thought experiments showed that, besides experimental science, he also valued logical reasoning (some writers think that he did not drop objects from the Leaning Tower of Pisa to demonstrate his ideas of falling objects). Einstein developed the Theory of Special Relativity from a thought experiment about running alongside a photon of light, while the Theory of General Relativity was developed from imagining a man in a falling lift. Heisenberg's quantum mechanics, Schrodinger's wave equation (and his famous cat thought experiment!) are all examples of rationalistic thinking that produced significant advances in science. In all of these instances, those scientists did not conduct any experiment to obtain data to develop or support their ideas. They all used rigorous mathematics in their work. Mathematics surpassed mechanism![14] Rationalism and *a priori* are the bases for deduction, a reasoning tool in science.

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[13] Gendler, T.S., 1998. Galileo and the indispensability of scientific thought experiment. The British Journal for the Philosophy of Science, 49(3), pp.397-424.

[14] Perepelitsa, D.V., 2006. Transitions of Physics: Rationalism and Empiricism.

Induction

Induction is a method of reasoning where individual ideas, facts or concepts are used to develop a general rule or conclusion. It is derived from emprícism.

The inductive method

According to inductive reasoning, a set of individual propositions are used to derive a general conclusion. The conclusion goes beyond the information in each of the underlying propositions. This is the process of **generalisation**. Through induction, general laws or principles are derived from observations of particular instances[15]. An example of inductive reasoning is as follows:

- Observation: All swans that I have observed are white.
- Inference: Therefore, all swans are white.

Inductive reasoning in science

Inductive reasoning has produced many grand ideas in science, such as the Cell Theory or the Big Bang Theory. Consider the following statements about the Cell Theory:

- Observation 1: All plants are composed of cells.
- Observation 2: All animals are composed of cells.
- Observation 3: All single-celled organisms are composed of cells.
- Inference: All living things are composed of cells*

*strictly, this inference needs another inductive inference: all plants are living; all animals are living; all single-celled organisms are living. Therefore, it can be inferred that plants, animals and single-celled organisms are living. It also assumes that plants, animals and single-celled organisms are the only living things on Earth.

The theories developed through inductive reasoning are broad explanations for a number of related phenomena. They are held to be true until proven otherwise.

Newton's Principia is a set of inductive arguments which establish that 'impenetrability, mobility, and impetus of bodies, and the laws of motion and the law of gravity' are features of every system in the universe (Miller, 2009). Newton could not possibly have observed every celestial body and everything in motion. Newton described four rules of induction[16]:

- Rule 1: We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances.
- Rule 2: Therefore, to the same natural effects we must, as far as possible, assign the same causes.
- Rule 3: the qualities of bodies, which admit neither intensification nor remission of degrees, and which are found to belong to all bodies within the reach of our experiments, are to be esteemed the universal qualities of all bodies whatsoever.
- Rule 4: In experimental philosophy, we are to look upon propositions inferred by general induction from phenomena as accurately or very nearly true, notwithstanding any contrary hypothesis that may be imagined, till such time as other phenomena occur, by which they may either be made more accurate, or liable to exceptions.

These propositions became fundamental laws in physics. Regarding inductive reasoning and his discoveries, Newton said[17]

> 'In this philosophy, propositions are deduced from the phenomena and are made general by induction. The impenetrability, mobility, and impetus of bodies, and the laws of motion and the law of gravity have been found by this method. And it is enough that gravity really exists and acts according to the laws that we have set forth and is sufficient to explain all the motions of the heavenly bodies and of our sea.'

The web resource below explains how inductive thinking was behind the development of Newton's laws of motion and gravity.

Web resource: Miller, D.M., 2009. Qualities, properties, and laws in Newton's induction. Philosophy of Science, 76(5), pp.1052-1063.

Criticism of induction

Sir Karl Popper, an Austrian-British philosopher, rejected inductivism, claiming that for induction to be true, every instance of its inference must be true. Since it is virtually impossible to claim that every inductivist inference will always be true, critics of inductivism have suggested that it is not a relevant reasoning tool in science. For example, before Europeans arrived in Australia, it was thought that all swans were indeed white. Early European explorers to Western Australia spotted the first recorded sightings of black swans. A strict interpretation of inductive reasoning would imply that the inference was wrong. However, rather than discarding the proposition altogether, a better approach would be to modify it to state 'most swans are white'. Thus, the original proposition is still valid. It is not necessary for inductivist inferences to be true in all instances. It is, however, important that those inferences are true most of the time. Hence, if a theory explains most, but not all, observations, then that theory is scientifically valid. Observations that are not supported by those inferences are may be exceptions or anomalies. Although Newton's Laws of Motion are true, those laws cannot describe the motion of objects moving close to the speed of light precisely. The physics of objects moving in those conditions are 'exceptional' in Newtonian physics. Einstein's Theory of Special Relativity provide explanations where Newton's Laws cannot. Thus, these two theories explain the motion of objects under different circumstances, and both are equally valid. In general, scientific theories and paradigms explain most observations and a few discrepant observations will not invalidate those theories[18,19].

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[15] Rothchild, I., 2006. Induction, deduction, and the scientific method. Soc. study Reprod.

[16] Shapiro, A.E., 2004. Newton's" experimental philosophy". Early Science and Medicine, 9(3), pp.185-217.

[17] Isaac Newton, The Principia: Mathematical Principles of Natural Philosophy, trans. I. Bernard Cohen and Anne Whitman (Berkeley,1999), 943.

[18] Rothchild, I., 2006. Induction, deduction, and the scientific method. Soc. study Reprod.

[19] Purtill, R.L., 1967. Kuhn on scientific revolutions. *Philosophy of science*, *34*(1), pp.53-58.

Another objection was that inductive reasoning might produce false inferences, even if all of the underlying propositions are true. Consider the following argument:

- Observation 1: Cows are mammals
- Observation 2: Kangaroos are mammals
- Inference: Cows are kangaroos

Although this argument is very simplistic*, it is evident that linear reasoning such as this can lead to problematic conclusions. For example, the fact that mutations of the *BRCA* genes are associated with breast cancer does not mean that those mutations cause breast cancer or that breast cancer formation is a certainty in women with those genetic mutations. Indeed, many women with mutations in the *BRCA* genes will not develop breast cancer.

*Even from a philosophical perspective, this inference is incorrect (it incorrectly applies the rules of philosophical reasoning). However, that discussion is beyond the scope of this guide.

Deduction

Deduction is another form of scientific reasoning and is based on rationalism. It produces explanations by **deriving** specific conclusions from general laws, principles or theories. The deductivist school of reasoning was firmly established by Sir Karl Popper and popularised by Sir Arthur Conan Doyle's fictional character, Sherlock Holmes. In science, the deductivist approach is more recent than the inductivist approach.

The deductive method

Deductive reasoning has produced a powerful method of scientific inquiry known as **hypothesis testing**. Deductive reasoning and hypothesis testing are commonly used in high school science experiments. It starts with a general theory, which is used to derive hypotheses. Hypotheses are predictive statements that are tested in controlled experiments or other observations. The results of those investigations are used to either support or refute the scientific hypothesis.

- Condition: If an angle measures between 90° and 180°, then it is an obtuse angle.
- Observation: Angle A = 120°.
- Deduction: A is an obtuse angle.

Deductive reasoning in science

J.J. Thomson's work with cathode rays is an example of the deductivist approach in science. Through a series of experiments, he showed that

- Cathode rays are negatively-charged.
- The negative charge of the cathode rays is due to negatively-charged particles called electrons.
- Electrons are subatomic particles that are about 1/1000 times smaller than hydrogen atoms.

Thus, from a general concept (cathode rays), J.J. Thomson derived specific knowledge about electrons.

Modus tollens and hypothesis testing

When making inferences from observations, two main reasoning tools may be applied: *Modus ponens* (method of affirming) and *modus tollens* (method of denying). *Modus tollens* is the basis of falsifiability, a method of testing scientific hypotheses. *Modus tollens* begins with an accepted premise (or theory), which is often stated as a predictive statement (if …then). It then attempts to make an inference with a 'negative' observation. For example,

- Premise: if there is no smoke, there is no fire
- Observation: There is no smoke.
- Inference (*modus tollens*): there is no fire.

Such reasoning was the basis falsifiability and the use of null hypotheses in hypotheses testing. In this approach, a null hypothesis is developed from the scientific hypothesis. After testing the null hypothesis using statistical tools, rejection of the null hypothesis results in the acceptance of the scientific hypothesis (and vice versa).

Criticism of deduction

For deductivist conclusions to be correct, the theories on which they are based must also be true. This is not always the case. The theories on which deductive hypotheses are based are often the products of inductive reasoning. This relationship can result in circular arguments (cannot be proven) or false conclusions. One example that illustrates this is the link between autism and vaccination (refer to the web resource indicated below).

- Historically, some vaccines contained a mercury-based preservative called thimerosal.
- Mercury poisoning is associated with symptoms that are similar to autism-spectrum disorder.
- Conclusion: Vaccines cause autism

Numerous scientific tests have shown that thimerosal is a safe preservative. Despite this, amid public speculation, thimerosal is no longer used as a preservative in vaccines. There are many different mercury compounds and they vary widely in their toxicity. Methylmercury, an environmental organomercury compound is very toxic to humans, while some other forms of mercury are well-tolerated by humans. However, the public often assumes that mercury is a single substance[20]. Thus, although the deductive conclusion described above is correct, the incorrect assumptions make the conclusion invalid.

To avoid such erroneous conclusions, Popper suggested that deductive reasonings should be based on the principle of falsifiability. Falsifiability has become the standard method of hypothesis testing.

Newton was a critic of deduction and hypothesis-based investigations. He wrote[21]

> 'I have not as yet been able to deduce from phenomena the reason for these properties of gravity, and I do not feign hypotheses. For whatever is not deduced from the phenomena must be called a hypothesis; and hypotheses, whether metaphysical or physical, or based on occult qualities, or mechanical, have no place in experimental philosophy.'

Web resource: Baker, J.P., 2008. Mercury, vaccines, and autism: one controversy, three histories. American Journal of Public Health, 98(2), pp.244-253.

Video resource: Deductive reasoning vs. Inductive reasoning

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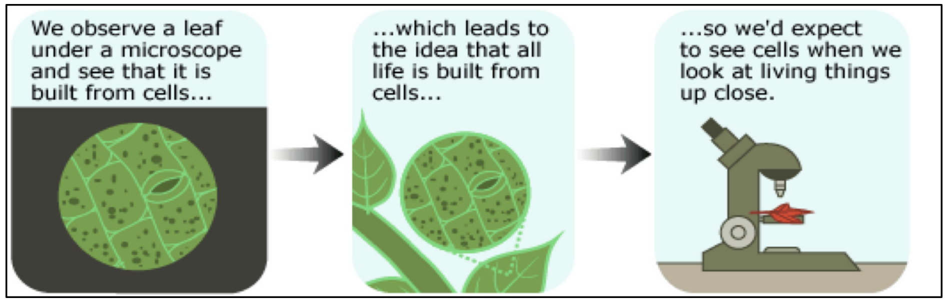
[20] Baker, J. P. (2008). Mercury, Vaccines, and Autism: One Controversy, Three Histories. *American Journal of Public Health*, *98*(2), 244–253.

[21] Newton to Cotes, 28 March 1713, Newton, The Correspondence of Isaac Newton, ed., H. W. Turnbull, J. F. Scott, A. Rupert Hall, and Laura Tilling, 7 vols. (Cambridge,1959-77), 5: 398-399.

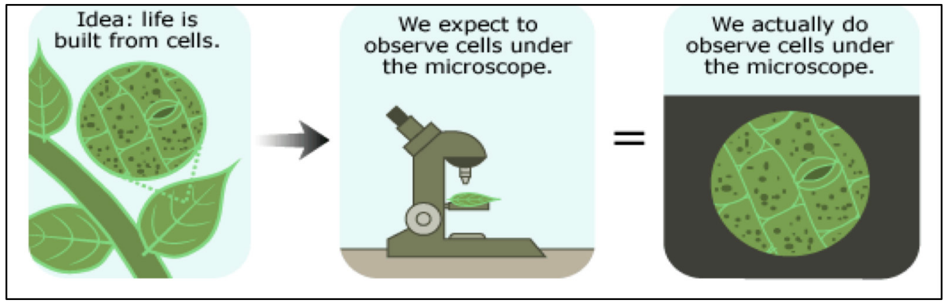
Induction and deduction in modern science

Both induction and deduction are complementary reasoning tools used in modern science. Inductive reasoning produces general principles that are used to construct theories of natural phenomena. Deductive reasoning provides avenues for verification of theories, mainly through hypothesis testing. For example, genome sequencing projects use inductive reasoning to identify and characterise genetic elements in the genomes of various organisms. This information can be extrapolated to identify some genomic features that are common to the species, genus and phylum that the organism belongs to. Deductive reasoning can be used to determine the functions of gene families and, perhaps, be used in genetic manipulation experiments. The following figure[22] shows inductive and deductive reasoning in Cell Theory.

Induction



Deduction



The panel above illustrates the inductive process, while the panel below illustrates the deductive process. In induction, discrete observations, such as the microscopic observation that leaves are made up of cells is generalised in the Cell Theory. In deduction, a hypothesis is developed from the Cell Theory: Since all life is composed of cells, then a leaf is composed of cells, because a leaf is alive. This inference is subsequently confirmed in experiments. In this manner, induction and deduction are integral cogs of the modern scientific process.

Apart from induction and deduction, there are other modes of reasoning and logic. Ultimately, the type of reasoning used in science investigations is not as important as how observations are analysed to develop conclusions.

Activities

Activity 1 and Activity 2 in the Appendix explore the application of inductive and deductive reasoning in science.

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[22] The core of science: Relating evidence and ideas. Understanding Science. University of California Museum of Paleontology. 3 January 2019

Law of Parsimony/Occam's razor

Occam's razor is a reasoning tool that is used to select a theory from a set of competing theories that are available to explain some natural phenomenon. Occam's razor is attributed to the English friar, William of Occam. There are two statements in his works that typify the razor:

- Plurality must never be posited without necessity.
- What can be explained by the assumption of fewer things is vainly explained by the assumption of more things.

Statements like these have been attributed to other thinkers, including Aristotle, Sir Isaac Newton, Sir Bertrand Russell and Albert Einstein. Aristotle said, "We may assume the superiority, other things being equal, of the demonstration which derives from fewer postulates or hypotheses." Newton claimed that "We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances. Therefore, to the same natural effects we must as far as possible, assign the same cause".

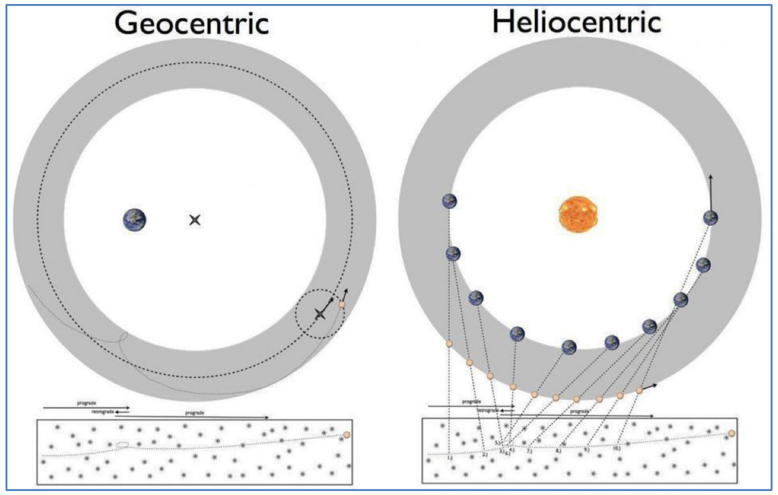
The word razor is an analogy to the process of 'shaving away' unwanted arguments when deriving conclusions. In modern science, Occam's Razor has been replaced with the term 'parsimony'.

Law of Parsimony

The Law of Parsimony describes an approach for choosing the simplest scientific argument that explains observations. It states that **'other things being equal, simpler explanations are generally better than more complex ones'**. The criterion, simplicity, is quite difficult to explain. However, it is generally accepted that simplicity in scientific explanations refers to those that

- Make fewer assumptions in their formulation
- Result in fewer exceptions

Therefore, when presented with two or more competing theories, the one that simplest should be selected. An example of parsimonious reasoning is the selection of the heliocentric model of the solar system. This model holds that the sun is at the centre of the solar system and is encircled by the planets that revolve around it. This model was first proposed by the Greek astronomer, Aristarchus of Samos, in the third century B.C. However, it fell out of favour and Ptolemy's geocentric model (where the Earth is considered to the centre of the solar system and the Universe) became the established model of planetary movement. However, there were problems with the geocentric model from the outset – the model could not account for the apparent retrograde motion of Mercury and Venus. To explain these contradictions, Ptolemy introduced the concept of epicycles ('circles within circles') in the orbits of the planets (deferents), with the Earth offset from the centre. Despite its complexity, there were errors in its predictions of planetary positions by several degrees, or by an angular distance larger than the diameter of the full Moon. The heliocentric model, which was revived in the 16th century by the Polish astronomer Copernicus, did not include the idea of epicycles. Yet, it was able to account for all of the predictions of the geocentric models. In that respect, the heliocentric model was more parsimonious (simpler) than the geocentric model. Subsequent astronomical data confirmed the validity of the heliocentric model of the solar system.



The figure on the left shows the geocentric model of the solar system, while the figure on the right shows the heliocentric model. The inset below each model shows the transit of a planet in retrograde motion against a backdrop of stars. The geocentric model requires the additional complexity of epicycles to account for the retrograde motion, while the simpler heliocentric model does not[23].

There are other examples in science where parsimony has resulted in the acceptance of simpler theories, including thermodynamics (caloric theory vs. mechanical theory of heat) and quantum theory (Bohr model of the atom vs. quantum physical models). Parsimony is used in evolutionary biology to establish phylogenetic (evolutionary) relationships between groups of organisms. For example, as shown in the figure below, the most parsimonious evolutionary model that explains the relationship between the three species of hummingbirds is the simplest one (which suggests the fewer genetic changes are required to produce the observed evolutionary changes).

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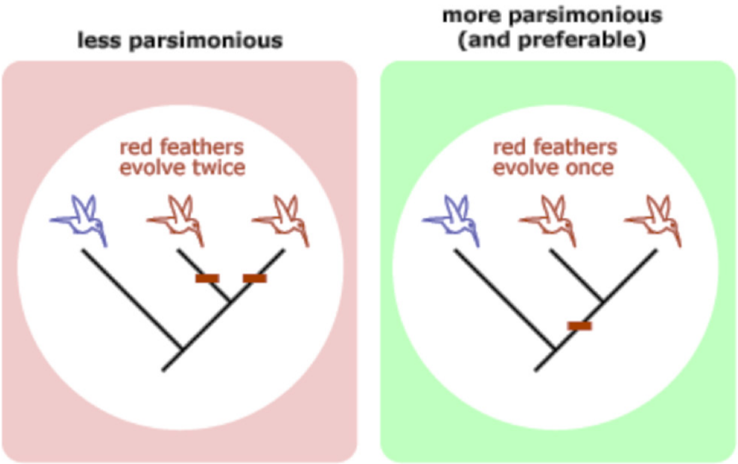
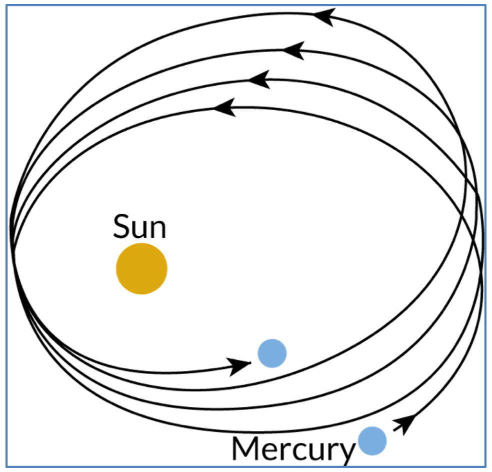
23 Siegel, Ethan (2018). What Separates A Good Scientific Theory From A Bad One?



In this example[24], two separate models are shown for the evolution of red feathers in two species of humming birds. The model on the left requires 200 genetic changes, while the one on the right requires only 70. Thus, all else being equal, the model on the right more parsimonious than the one on the left and is the preferred model.

Criticism of Parsimony

The concept of parsimony is not universally accepted. Occam's razor can only be applied when experimental evidence or observations support the competing ideas, and when those ideas differ in their complexity. If the competing ideas are equally valid and complex, Occam's razor cannot be applied. There are many instances of simpler theories being proven wrong or inaccurate with subsequent evidence. For example, Newton's Law of Universal Gravitation is a simpler explanation for planetary motion compared to Einstein's theory of general relativity. However, Einstein's General Relativity is more accurate. General Relativity was able to provide an explanation for Mercury's unusual orbit around the sun, which could not be explained by Newton's Law of Gravitation.



Mercury's elliptical orbit around the sun changes over time. Einstein explained this phenomenon using his ideas of General Relativity[25], which was not possible with Newton's Law of Gravitation.

[Web resource: Law of Parsimony]

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[24] "Competing ideas: Other considerations." Understanding Science. University of California Museum of Paleontology. 3 January 2019

[25] Will CM. New General Relativistic Contribution to Mercury's Perihelion Advance. Physical Review Letters. 2018;120(19):191101

Falsifiability

Falsifiability is another reasoning tool used in science. The word falsifiability refers to the practice of disproving ideas. This is contrary to the common notion that science tries to prove the truth of its ideas. Falsifiability is based on the philosophy of skepticism. According to skepticism, truth and certainty of knowledge are not attainable by humans. Instead, by being critical and skeptical, it is possible to identify and eliminate untruths and falsehoods, thus bringing us closer to the truths behind our inquiries. Falsifiability builds on that principle and forms the basis of an important inquiry process – hypothesis testing. Falsifiability was championed by Sir Karl Popper[26].

Falsifiability and hypothesis testing

The principle of falsifiability imparts rigidity to the construction and use of hypotheses in science. Hypotheses are deductive (hypothesis testing is also referred to as a hypothetico-deductive approach). Hypotheses are operative statements used to design, conduct and evaluate scientific inquiries. Well-framed hypotheses possess the following qualities:

- They are testable (in experiments or verifiable through observations).
- They are predictive (for example - they predict particular outcomes if some conditions are met).
- They are explanatory (for example - they are based on sound scientific concepts).

To apply falsifiability to hypothesis testing, inquiries must contain the following three elements:

1. Generating a scientific hypothesis.
2. A method for rejecting (falsifying) the scientific hypothesis.
3. A method for accepting the scientific hypothesis.

The scientific hypothesis (step 1 above) is generated from scientific theories, laws and paradigms. The following steps are followed to either reject (step 2 above) or accept (step 3 above) the hypothesis:

- A null hypothesis (that falsifies the scientific hypothesis)
- An alternate hypothesis (that falsifies the null hypothesis and is similar to the original scientific hypothesis)

Only the null hypothesis is subject to statistical tests. Consequently, if the null hypothesis is rejected, then the alternate hypothesis is accepted. This then supports the original scientific hypothesis. Conversely, acceptance of the null hypothesis invalidates the original scientific hypothesis.

In this manner, falsifiability enables scientists to get closer to the truth of their discoveries (by rejecting that which is false or cannot be substantiated).

Criticism of falsifiability

The falsifiability approach of Popper depicts a clean delineation between falsifiable ideas and those that are not. Falsifiable ideas are considered to be scientific, while other ideas are not scientific. For example, since the basic tenets of Intelligent Design and astrology cannot be falsified, these areas are not science. Falsifiability provides a characteristic of scientific knowledge (refer to epistemology). However, in many areas of scientific research, falsifiability is not always possible. Some of the scientific ideas that are being developed are so complex or so new that it is not possible to falsify them using experiments and observations. For example, the Theory of General Relativity was only validated many years after the theory was published[27]. As another example, Peter Higgs and his colleagues proposed the existence of the Higgs Boson in 1964, but was experimentally verified by scientists at CERN in 2012. Therefore, even though these ideas were not falsifiable when they were initially proposed, they were subsequently validated through scientifically-generated data. Hence, there appears to be a grey area where the principle of falsifiability may not apply to scientific ideas. Disciplines such as evolutionary biology, geology and astronomy contain ideas that are scientific but not falsifiable[28]. Popper himself initially rejected Darwin's Theory of Evolution by Natural Selection but reversed his position later.

Video resource: How can I know anything at all?

Video resource: Karl Popper, Science, and Pseudoscience: Crash Course Philosophy #8

Activity

Activity 3 in the Appendix explores falsifiability in science.

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[26] Science as falsifiability

[27] Coles, P., 2001. Einstein, Eddington and the 1919 eclipse. arXiv preprint astro-ph/0102462.

[28] Popper and Evolution

Confirmation bias and theory-dependent observations

Since observations are vital to scientific inquiry, any factors that impact on the accuracy and impartiality of observations may influence the conclusions of those inquiries.

Confirmation bias

Confirmation bias refers to the tendency to search for, interpret, favour, and recall information in a way that confirms one's pre-existing beliefs or hypotheses. Some examples include:

1. N-rays[29]: In 1903, the French scientist, Prosper-René Blondlot, announced the discovery of N-rays, which he described as a new form of radiation released by both non-living and living things (he called them 'N' rays after the University where he performed his research – Nancy). At least 40 other people reported seeing the N-rays, and more than 100 scientists published 300 papers on this phenomenon (between 1903 and 1906). N-rays were an ephemeral thing: observed only as a corona around an electric discharge from certain crystals. They were only observed by the human eye, making them difficult to quantify. The American scientist Robert Wood visited Blondlot's laboratory to study the phenomenon himself. During one of the experiments, he surreptitiously removed the crystal that supposedly generated the N-rays, after which Blondlot failed to notice the absence of N-rays - the N-rays did not vanish when the crystal was removed! This discovery occurred at a time in France when researchers were trying to establish the scientific basis of spirituality. It was also a time when great strides were made in the field of atomic physics. N-rays appeared to satisfy that need for a 'scientific explanation' of spirituality and the striving for scientific esteem.
2. Water memories: Jacques Benveniste published a paper in the journal Nature[30] about an experiment involving the efficacy of a diluted reagents. He explored the degranulation of a type of immune cell known as a basophil. In the presence of an antibody called anti-IgE, basophils undergo a reaction called degranulation. This is the basis of the allergic response in mammals. In his paper, Benveniste reported that highly diluted solutions of anti-IgE provoked the same degranulation reaction as did the stronger solutions of the reagent. He suggested the even though the highly dilute solutions of anti-IgE did not contain the solute, their ability to trigger degranulation was due to the water (solvent) molecules retaining the memory of the shape of the anti-IgE molecules. The researchers indicated "Therefore we propose that none of the starting molecules is present in the dilutions beyond the Avogadro limit and that specific information must have been transmitted during the dilution/shaking process. Water could act as a 'template' for the molecule, for example by an "infinite hydrogen-bonded network", or electric and magnetic fields. At present we can only speculate on the nature of the specific activity present in the highly diluted solutions". A subsequent blind study failed to replicate his findings[31]
3. Lunacy: There are many stories and myths about the moon's influence on human behaviour. Domestic violence, drug overdoses and, of course, emergency-room visits have all been correlated with the full moon. Our own experiences have confirmed the theory when it happens, but when it does not fit the theory we tend to ignore it or forget about it (web resource – Dr Karl). A meta-analysis of 31 studies that explored the link between lunar phases and human behaviour concluded that, even when there were statistically significant correlations, the effect sizes were negligible[32]. The authors concluded that 'Alleged relations between phases of the moon and behavior can be traced to inappropriate analyses, a failure to take other (for example - weekly) cycles into account, and a willingness to accept any departure from chance as evidence for a lunar effect'.

Web resource: Lee, Chris (2010) Confirmation bias in science: how to avoid it

Web resource: Dr Karl – Can a full moon affect behaviour?

Theory-Dependent Observations

Observations are said to be 'theory-dependent' when they are affected by the theoretical presuppositions held by the investigator. Some examples of presuppositions that may influence observations include:

- Past experiences, including research experiences.
- Social, political and scientific views.
- Performing inquiries with the expectations of specific outcomes.

It is reasonable to assume that all scientists hold presuppositions that influence their observations and analyses of experimental results. Philosophers have suggested that such presuppositions will affect both inductive and deductive reasoning, as observations are used as evidence in both types of reasoning. However, peer-review of scientific research often identifies such biases and ensures the robustness of the scientific process. While it may influence observations and interpretations, such presuppositions may also allow researchers to gain deep insights into new, unexplored data. In these instances, theory-dependent observations produces the 'expert mind'. For example, an expert radiographer may be able to identify anomalies in an X-ray image that the novice radiographer may not. Similarly, an experienced scientist may draw a different conclusion after analysing a dataset, compared to a novice scientist. In the history of science, theory-dependent observations have given rise to alternative explanations of phenomena and, sometimes, to significant breakthroughs in our understanding. The following table provides examples of such breakthroughs:

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[29] Nye, M.J., 1980. N-rays: An episode in the history and psychology of science. Historical studies in the physical sciences, 11(1), pp.125-156.

[30] Davenas, E., Beauvais, F., Amara, J., Oberbaum, M., Robinzon, B., Miadonnai, A., Tedeschi, A., Pomeranz, B., Fortner, P., Belon, P. and Sainte-Laudy, J., 1988. Human basophil degranulation triggered by very dilute antiserum against IgE. Nature, 333(6176), pp.816-818.

[31] Maddox, J., Randi, J. and Stewart, W.W., 1988. "High-dilution" experiments a delusion. Nature, 334(6180), p.287.

[32] Rotton, J. and Kelly, I.W., 1985. Much ado about the full moon: A meta-analysis of lunar-lunacy research. Psychological Bulletin, 97(2), p.286.

Field	Contrasting conclusions
Mechanics	• Newton: mass is constant (inertial mass) • Einstein: mass changes with velocity (relativistic mass) • Aristotle: larger objects fall faster through the same medium • Galileo: in the absence of resistance (of the medium through which they are travelling), all objects fall at the same speed.
Astronomy	• Ptolemy: saw a moving sun across the sky – the geocentric model of the solar system • Copernicus: saw a stationary sun but a revolving Earth – the heliocentric model of the solar system
Chemistry	• Priestly: combustion is caused by a combustible substance called phlogiston • Lavoisier: Combustion is the result of the reaction of substances with oxygen

Paradigm shifts and scientific revolutions

The American scientist and philosopher, Thomas Khun, explored the causes of significant shifts in scientific understanding. He elaborated his ideas in a significant publication[33], which is an important contribution to the philosophy of science. **The scientific paradigm refers to concepts and theories that are accepted by the scientific community because of their effectiveness in explaining natural phenomena**[34]. It also extends to the epistemology and process of science.

Normal and puzzle-solving science

Kuhn examined the scientific paradigm through the ages and defined two types of scientific endeavours:

- **Normal science**: Kuhn's normal science refers to the day-to-day practice of science and "development-by-accumulation". It involves scientific observations and experiments, generating data and observations, as well as testing hypotheses.
- **Puzzle-solving science**: This refers to episodic upheavals in science, where continuity is interrupted by periods of scientific revolution. This phase contains scientific observations that cannot be explained by contemporary paradigms, as well as anomalous results and hypotheses that are not supported by experimental observations.

According to Kuhn, normal science does not produce scientific revolutions. Instead, revolutions are precipitated by puzzle-solving science. Over time, observations which cannot be explained by contemporary paradigms emerge. To explain these discrepant observations and anomalies, new theories need to be developed. These new theories then constitute paradigm shifts. Furthermore, Khun identified a three-step process by which scientific revolutions occur:

1. **Normal science** – Normal scientific investigations occur within the purview of contemporary scientific paradigms. Normal science may be preceded by the **pre-paradigmatic stage** - a period of somewhat inchoate and directionless
2. **Crisis** – Over time, anomalies and unsupported observations begin to accumulate. The contemporary paradigms are critically evaluated, and there is an increase in puzzle-solving science activities.
3. **Paradigm shifts** – Newer theories are proposed to account for the puzzle-solving scientific observations.

Contemporary paradigm	Anomalies	Paradigm shift
Geocentrism	• Retrograde motion of planets • Orbit of Jupiter's moons • Phases of Venus	Heliocentrism
Inheritance of Acquired Characters – experiences of a lifetime are passed on to the next generation and evolution drives towards increased complexity	• Experiences within lifetime are not inherited (e.g. amputees produce children with normal limbs) • Complex organisms are not formed from simpler ones	Evolution by Natural Selection
Miasma Theory of Disease - diseases are caused by 'bad airs'	• Pasteur's experiments with vaccination • Koch's postulates about microbes and diseases	Germ Theory of disease

Types of paradigm shifts

Paradigm shifts and scientific revolutions generally take one of two forms[35]:

1. Theory replacement – New theories replace old theories (for example - geocentrism is replaced with heliocentrism)
2. Theory modification – New theories are added to contemporary theories. For example, Newton's Laws of motion and gravitation, which extended Galileo's and Kepler's discoveries, were themselves extended by Einstein's Theories of Special and General Relativity. Einstein's theories did not replace Newton's Laws, but are used in those special situations that demand high levels of accuracy or when classical mechanics fail (for example - movement at light speed).

Web resource: An Overview of Thomas Kuhn's The Structure of Scientific Revolutions

Web resource: Kuhn, T.S., 1970. The structure of scientific revolutions, International Encyclopaedia of Unified Science, vol. 2, no. 2.

Further discussions on paradigm shifts

Lavoisier and oxygen

What Lavoisier announced in his papers from 1777 on was not so much the discovery of oxygen as the oxygen theory of combustion. That theory was the keystone for a reformulation of chemistry so vast that it is usually called the chemical revolution. Oxygen was not discovered by one single person through a single simple act assimilable to our usual concept of seeing.

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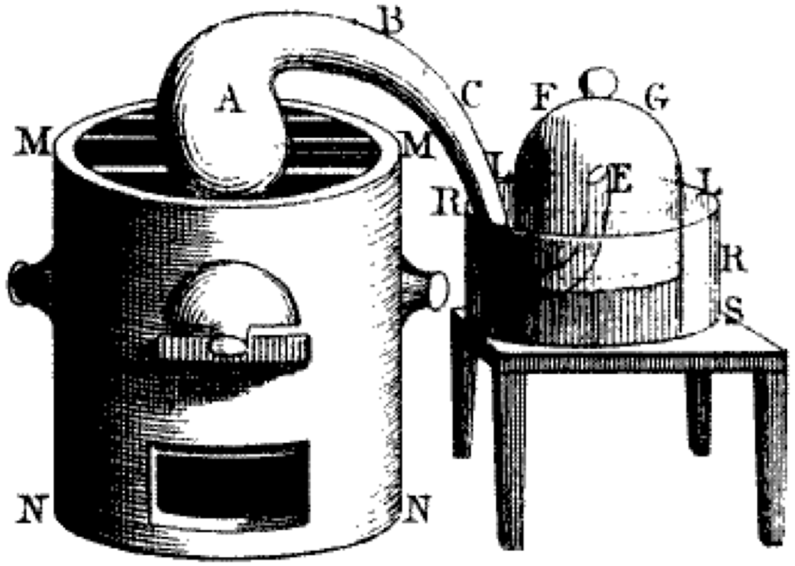
[33] Khun, T., 1962. The Structure of Scientific Revolutions University of Chicago Press.

[34] Shapere, D. (1971). The paradigm concept. Science, 172, 706-9

[35] Enfield, P., 1991. Realism, empiricism and scientific revolutions. Philosophy of Science, 58(3), pp.468-485.

During Lavoisier's time, chemistry was not the scientific discipline that it is today. Many aspects of chemistry were closely associated with alchemy – a semi-scientific approach to transforming substances. The concepts of chemistry were still mired in the legacy of the Greek philosophers. Aristotle's four elements of earth, air, fire, and water has been slowly worked on by medieval alchemists. In the 18th century, the German scientist Georg Ernst Stahl contributed to a shifting paradigm in chemistry by introducing the concept of phlogiston. Every combustible substance contained a universal component of fire (Phlogiston). For example, charcoal lost weight when it burned due to the loss of its phlogiston component to the air.

The Emergence Of Anomalies - When metals were strongly heated in air, the resulting calyx (residue of burning) weighed more than the original metal, not less. The British scientist, Joseph Priestley, collected the gas released by heated red oxide of mercury. This gas enhanced respiration and caused candles to burn longer. He believed it was because of the gas is free of phlogiston. Priestley named the gas as 'dephlogisticated air' Lavoisier repeated Joseph's experiment proposed a new theory of combustion that excluded phlogiston. Combustion, he said, was the reaction of a metal or an organic substance with that part of the common air he termed 'eminently respirable.' Later he found most acids contained eminently respirable air and coined the term oxygène, from the two Greek words for an acid generator. A new era of chemistry based on fact and observation rather than idea and hypothesis has begun.



Lavoisier performed his classic twelve-day experiment in 1779 which has become famous in history. First, Lavoisier heated pure mercury in a swan-necked retort over a charcoal furnace for twelve days. The neck of the flask was inserted into a bell jar, which contained some water. When heated, the silvery mercury turned into a red power (which was called the calyx). At the end of the combustion reaction, Lavoisier noticed that about one-fifth of the air in the bell jar had been used up. The gas remaining in the bell jar did not support life or burning. Lavoisier called this residual gas azote. (Greek 'a' and 'zoe' = without life). It was known that if the calyx was further heated, gas would be released. In the next part of this study, Lavoisier heated the calyx and measured the volume of the gas that was released. His results showed that the heated calyx released the same volume of gas that disappeared from the bell jar in the previous experiment. He found that the gas released from the heated calyx caused flames to burn brilliantly, and small animals were active in it. Finally, when he mixed the gas released by the heated calyx with the residual gas in the bell jar, Lavoisier realised that the mixture was identical to normal air. He concluded that air consisted one part of oxygen (which supports combustion and life) and four parts of azote (later called nitrogen).[36]

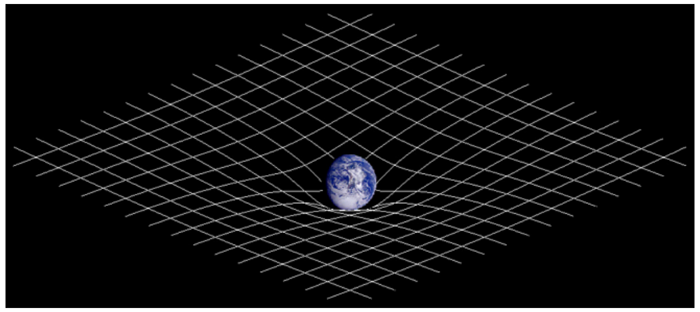
Web resource: The chemical revolution

Web resource: The logic of phogiston,

Einstein and General Relativity

Aristotle's believed that time and space are absolute and there is an absolute rest frame - the Earth (that is - the Earth is always at rest). Galileo and Copernicus discovered anomalies such as relative motion, and that the Earth is not the centre of the solar system. Newton, through the publication of Principia, started a new paradigm. For the first time, there were universal principles. An apple falling on Earth and the planets orbiting around the sun were now subject to the same laws. Heavens were no longer so mysterious, no longer beyond the grasp of the human mind. Einstein's publication of the General Theory of Relativity in 1915 has shifted the paradigm from Newtonian physics where time and space are absolute, and gravity could be calculated but not understood. In Einstein's General Relativity, space and time fuse to form a 4-dimensional continuum. When describing relativity, the American physicist John Wheeler said

> 'Matter tells space-time how to bend and space-time tells matter how to move.'



This figure[37] depicts the curvature of space-time, as predicted by the General Theory of Relativity. Einstein conducted a thought experiment about a man who is in a falling lift. In that situation, the man would not feel his weight – weightlessness. He soon realised that acceleration and gravity are equivalent. This realisation was instrumental in reinterpreting gravity – from a non-contact force to a consequence of curvatures in space-time.

This shift is so profound it took decades for physicists to come to grips. The web resource '100 years of relativity' by Ashtekar includes a detailed discussion of this paradigm shift.

When Max Planck learned that Einstein was attempting to find a new theory of gravity to resolve the conflict between special relativity and Newtonian gravity remarked.

> 'As an older friend, I must advise you against it, for, in the first place you will not succeed, and even if you succeed, no one will believe you.'

Web resource: Space and time from antiquity to Einstein and beyond

Web resource: Ashtekar, A. ed., 2005. 100 years of relativity: space-time structure: Einstein and beyond. World Scientific.

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[36] Adapted from Lavoisier's discovery of the role of oxygen in combustion,

[37] Space-time lattice,

Wegener and continental drift

Alfred Lothar Wegener (1880–1930) was a well-known geophysicist, and explorer. Despite being regarded as the father of continental drift, he is not the first person to propose the theory. The web resource shown below explores how numerous scientists have addressed different aspects of the theory and blurred the existing paradigms. However, it was Alfred Wegener who put together a vast amount of geophysical, paleoclimatic, paleontological and geological data to show that the continents were once assembled in a single landmass, before breaking down and ‘drifting’ apart.

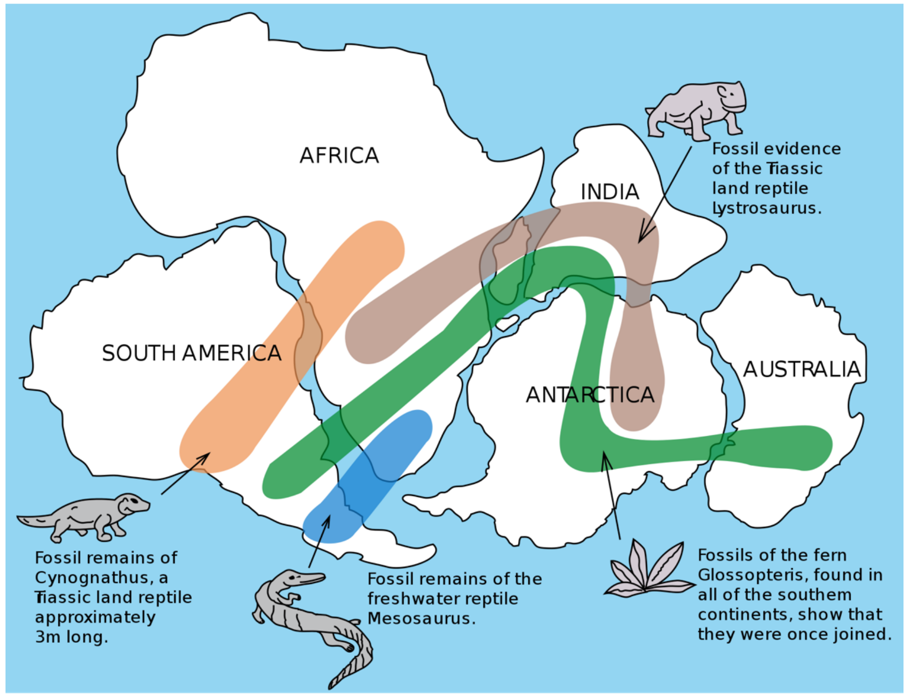

Figure of Pangea (a single landmass or supercontinent) that drifted apart to form present-day continental land masses. The complementary margins of the continental margins were the first clue to the existence of Pangea. Continental drift occurs because of plate tectonics – the geological instability caused by the turbulence of the mantle. The different coloured shaded areas shows regions of the indicated fossils, which was used by Wegener as further evidence of continental drift.[38]

Wegener’s theory was tenuous at first, as no convincing mechanism for drifting continents was evident. In 1929, Arthur Holmes suggested that the convective movements of the mantle may be responsible for continental drift[39] – this mechanism remains the prime candidate for the force that may drive the continental plates apart. However it is not till 1960 that Wegener’s theory gained significant attention. Wegener was dead by then – he had died in 1930 while on an expedition to determine the thickness of the polar ice sheets in Greenland. He was buried under the ice (now thought to be below 100 m of snow and ice). Later explorers, who found his ice grave, penned a tribute to Wegener:

> “He is found with wide eyes open and smiles about the fact that, even in death, corroborating his too visionary dream for his fixist and immobilist time by simply drifting on the continent”.

Web resource: Romano, M., Console, F., Pantaloni, M. and Fröbisch, J., 2017. One hundred years of continental drift: the early Italian reaction to Wegener’s ‘visionary’ theory. Historical Biology, 29(2), pp.266-287.

Web resource: Development of tectonic theory

McClintock and transposable elements

For a long time, genes were thought to occupy fixed locations on DNA. Barbara McClintock, in the late 1940s, discovered some genes are mobile and appeared to change their locations in the genome. She called them transposons or transposable genetic elements. In her research, McClintock examined how different corn kernels in a cob could have different colours, even though all the kernels on a cob were genetically identical. She discovered that some genetic elements could ‘jump’ from one location to the next. When these elements landed within genes that controlled the colour of the kernels, the colour of those kernels changed. Since this was a random event, the colour of the kernels was randomly altered.

A figure of a corn cob showing colour variations within the kernels. These colour variations are due to mobile genetic elements or transposons.[40]

Transposons are thought to be a significant cause of genetic variations/gene mutations in many organisms, including humans. However, the world was not ready for the idea of jumping genes and it took a long time for the concept of transposons to be accepted by the scientific community. McClintock was awarded the Noble prize in physiology or medicine in 1983, 35 years after her first publication on transposons. Transposons are a well-established concept in genetics and are known to regulate or influence many biological processes. They constitute more than 65% of the human genome! DNA is no longer a fixed structure but dynamic and ‘live’!

Video resource: Transposons

Video resource: Barbara McClintock

Web resource: Ravindran, S., 2012. Barbara McClintock and the discovery of jumping genes. Proceedings of the National Academy of Sciences, 109(50), pp.20198-20199.

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[38] Continental drift theory

[39] Arthur Holmes: Harnessing the Mechanics of Mantle Convection to the Theory of Continental Drift.

[40] Transposons.

Scientific developments in other cultures

In all cultures, humans have constructed knowledge by seeking explanations of empirical observations, and thus interpret and predict natural phenomena. Astronomy is probably the oldest of the sciences, and quite possibly, the first use of astronomy is navigation by the stars (stellar navigation). Henry Neeley noted

> 'The navigational use of the stars will continue to be a valuable asset for many years to come. In spite of all the scientific aids that have been developed to do the navigating by robot science, the ancient stars will still be a 'must' for navigator or pilot.'[41]

The web resource below compares the differences between western science and traditional knowledge. Why is it important to study to learn from each other (for example - Western and non-Western science)? Western scientific inquiries and traditional knowledge inquiries possess different characteristics. As described by Mazzocchi (2006),

> 'Western science is objective and quantitative as opposed to traditional knowledge, which is mainly subjective and qualitative. Traditional knowledge systems do not interpret reality on the basis of a linear conception of cause and effect, but rather as a world made up of constantly forming multidimensional cycles in which all elements are part of an entangled and complex web of interactions'

Web resource: Mazzocchi, F., 2006. Western science and traditional knowledge: Despite their variations, different forms of knowledge can learn from each other. EMBO reports, 7(5), pp.463-466.

Science educators have struggled with teaching scientific ideas that have originated in non-Western societies. While most contemporary paradigms in science are the products of Western thought, it has been more difficult to address non-Western scientific ideas in the science classroom. One obvious intersection between Western and indigenous science is in the area of ecological research, where indigenous knowledge (also known as Traditional Ecological Knowledge[42]) has contributed significantly to the scientific understanding of local ecosystems. Such links are more difficult to demonstrate in other areas of science. Some authors[43] have highlighted that the differences between Western and non-Western science may be due to the cultural differences in

- The relationship between people and their environments
- The systems of logic used to undertake inquiry

One fundamental issue that needs to be addressed is 'is science an invention of the Europeans, or has scientific inquiry also emerged in other cultures?' When viewed from the procedural perspective, the scientific process is a unifying concept and 'scientific thinking' is apparent in many cultures. Non-Western scientific inquiry possesses characteristics such as observing, questioning, predicting, inferring, problem-solving, modelling, experimenting and interpreting – features that are in common with Western science. There have been significant contributions in the areas of mathematics, engineering, navigation, military science, metallurgy, architecture, astronomy, geology, climatology, agriculture, medicine, biology and ecology[30]. Thus, Western science is one form of science that is practiced around the world. One key difference between Western and non-Western science is the mode of communication – non-Western science often relies on invisible and non-formal modes of communication (including the use of metaphors, symbols, myths and narratives). However, unlike other fields wherein cultural contributions remain distinct (for example - comparative art and comparative religion), science remains a unified endeavour in a dynamic environment where concepts are generated, subsumed and transmuted.

Aboriginal and Torres Strait Islander cultural observational knowledge

Australian astronomy

Many traditional Aboriginal cultures incorporate significant references to the sky and to astronomical phenomena. For example, many different Aboriginal cultures across Australia refer to the "Emu in the Sky". The web resource below (Aboriginal astronomy) provide more information about Aboriginal astronomy. Teaching resources for aboriginal astronomy may be found using the teaching resources links indicated below. Aboriginal Dreamtime stories describe eclipses, the rising and setting of the sun and moon and the positions of stars and planets. The web resources, 'Songlines and navigation in Wardaman and other Aboriginal cultures' and 'Australian Aboriginal Astronomy and Navigation', describe celestial navigation. For example, while ancient European astronomy focussed on the stars and planets, Aboriginal astronomy also explored the space between the heavenly bodies.

The night sky over the Atacama Desert in Chile, which shows many galaxies, such as the Milky Way, the small and large Magellanic Clouds, and Coalsack nebula (dark smear in the Milky Way). Australian Aborigines call this the 'emu in the sky'.[44]

Indigenous weather knowledge

For over 50,000 years, Aboriginal and Torres Strait Islander people have learned about the changing of the seasons, building an intricate knowledge of their environment. Different tribes categorised the weather according to natural environments and changes in flora, fauna. For example, in northern Australia, white Australians define two seasons (wet

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[41] Rao, J. (2008) Navigating By The Stars.

[42] Snively, G. and Corsiglia, J., 2001. Discovering indigenous science: Implications for science education. Science education, 85(1), pp.6-34.

[43] Ogawa, M., 1986. Toward a new rationale of science education in a non-western society. European Journal of Science Education, 8(2), pp.113-119.

[44] Emu in the sky.

and dry), while Aboriginal Australians have six (based on weather, tides, plant blooming and fruiting cycles, insect abundance and the breeding cycles and migrations of fishes, mammals and birds). The web resource shown below (Indigenous weather knowledge) explores indigenous weather knowledge.

Fire-stick farming

Explorers who were sailing around the Australian coast reported that the coastlines were dotted with fires. Peron, in 1802, sailing up Derwent in southeast Tasmania, said that

> 'Wherever we turned our eyes, we beheld the forests on fire.'[45]

There are several uses of burning:

- Signalling
- Ground clearing
- Hunting
- Regeneration of plant food
- Extending man's habitat
- Increase food supply

Web resource: Aboriginal astronomy

Web resource: Aboriginal astronomy can teach us about the link between sky and land

Teaching resource: Star stories of the dreaming

Teaching resource: Stories in the stars

Web resource: Norris, R.P. and Harney, B.Y., Songlines and navigation in Wardaman and other Aboriginal cultures. Journal of Astronomical History and Heritage.

Web resource: Dawes Review 5: Australian Aboriginal Astronomy and Navigation

Web resource: Indigenous weather knowledge. Australian Bureau of Meteorology

Greek astronomy

Ancient Greece produced many key thinkers in science and philosophy. The essence of their approach was to seek explanations for the things they observed in nature, such as the motions of the planets. Greek astronomy was influenced by the Babylonian, Chaldean and Egyptian civilisations, which also made major strides in astronomy. Greek astronomers employed principles of physics (parallax) and mathematics (geometry) to develop explanations for astronomical phenomena and conducted experiments to confirm their ideas. The philosopher, Aristotle, developed the geocentric model. This model was the predominant model of the solar system until the 16th century. The heliocentric model, which replaced the geocentric model, was also developed in the 3rd century BC in ancient Greece by the astronomer, Aristarchus. He was also able to measure the curvature of Earth and calculate the size of the Earth and the distance between Earth and the moon. Modern astronomy is based mainly on Greek astronomy. Ptolemy's contribution to astronomy (geocentrism) was part of the mainstream thinking for many centuries[46]. His work was translated into Arabic and was called Almagest (The great work).

Egyptian astronomy

Ancient Egyptian astronomy[47] was closely related to the religious and cultural practices of its people. It is thought that some of their star maps were developed to guide the journey of the spirits of the dead in their passage to the afterlife. Calendars were developed to schedule religious festivities and temple activities. The Egyptian calendar was the basis of the Gregorian calendar, which is still in use today[48]. Some features of Egyptian astronomy include:

- Tell time at night. These groups of stars, called decans, were used for telling time at night. Each group of stars rose forty minutes later each night. Observing the position of a group of stars relative to the day of the year would tell a person what time it was.
- Annual calendar. Ancient Egyptian's calendar had thirteen months because the twelve lunar months were not enough to make up a whole year. So, when the constellation of Sirius rose very late in the twelfth month, the thirteenth month began.
- Pyramids. The pyramids eastern and western sides run almost due north, and their southern and northern sides run almost due west. This kind of positioning could not have been done without using astronomy to find due north and south.

The Nabta Playa Calendar circle at Aswan. This astronomical feature was used as a solar calendar.

Web resource: ancient Greek astronomy

Web resource: Ancient Greek astronomy: the distance to the sun and the moon

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[45] Petty, A.M., 2012. Introduction to fire-stick farming. Fire Ecology, 8, pp.1-2.

[46] Ptolemy.

[47] Parker, R.A., 1974. Ancient Egyptian Astronomy. Phil. Trans. R. Soc. Lond. A, 276(1257), pp.51-65.

[48] Portal to the heritage of astronomy.

Asian cultural observational knowledge

Many Asian cultures also made significant contributions to scientific understanding. While their inquiry approaches were not driven by the philosophical underpinnings of Western science, Asian scientists sought to explain natural phenomena in similar conceptual frameworks.

Chinese science and traditional Chinese medicine

Historically, science in China was viewed from a practical perspective and to manage their large population. Many of their scientific discoveries were state-sponsored research and development that led to the development of various engineering and technological feats (for example - metallurgy, gun powder, printing, paper and irrigation). Compared to Western science, Chinese science did not focus on systems of reasoning and logic. Traditional Chinese medicine views the human being as existing in a harmonious relationship with its natural environment. Some techniques in pharmacology, herbal medicine and acupuncture have survived from Ming dynasty. Li Shizhen, gathered medical information from cultural observational knowledge from across China, he spent over 30 years to write the book of 'Compendium of Materia Medica'. The Compendium, a medical text including 1,100 illustrations and 11,000 prescriptions, set the foundation for Chinese medicine. The discovery of artemisinin for the treatment of malaria was described in ancient Chinese texts. The web resource below describes the development of artemisinin.

Web resource: Miller, L.H. and Su, X., 2011. Artemisinin: discovery from the Chinese herbal garden. Cell, 146(6), pp.855-858.

Islamic science and medicine

Islamic science flourished between the 7th and 15th centuries, when European centres of learning were in decline. Islamic science were the beneficiaries of scientific knowledge from many parts of the world, including India, Europe and other Middle Eastern nations. The Islamic world produced several leading scientific thinkers, including Gerber (Persian chemist, astronomer, engineer, geographer, philosopher, physicist, pharmacist and physician), Avicenna (Persian astronomer and physician), Rhazes (Persian polymath, physician, alchemist, and philosopher), Adhazin (Iraqi mathematician, astronomer, and physicist) and al-Khwarizmi (Persian mathematics, astronomy, and geography). Many of the discoveries of these scientists were translated into European languages and stimulated scientific discoveries in the West[49]. As Islamic rulers invaded countries from the Far East to Europe, they absorbed local knowledge about science, medicine, philosophy and technology. Books from Greek and Roman civilisations were translated into Arabic. Scholars examined reasoning and logic (particularly empiricism), as well as experimental science. Islamic medicine was based on the words of the founder of Islam 'Make use of medical treatment, for Allah has not made a disease without appointing a remedy for it, except for one disease: old age'[50]. Books like 'Marvels of Creatures and Strange Things Existing' by al-Qazwini was written in 14th century. In that book, al-Qazwini describes the following treatment – 'The viper is skinned and dried [to become] a hair-removal paste. If its ashes are mixed with vinegar and smeared on erysipelas [a skin infection] they cure it, and haemorrhoids too.'

Illustrations from the book by al-Qazwini. This book explores a variety of topics, such as human anatomy, mythical creatures; plants and animals, constellations of stars and zodiacal signs[51].

Web resource: Islamic medicine

Perspectives

Science is the product of our innate sense of curiosity and our quest for meaning. Although modern science is descended from many different philosophical traditions, scientific practice differs from other fields of inquiry in the way it develops knowledge. Scientists employ various approaches to investigate and construct explanations of natural phenomena. No matter what those approaches may be, scientific investigations are united by the need for evidence, logical reasoning and peer evaluation. Scientific research involves extended periods of purposeful investigations conducted in the relentless pursuit of answers to questions. Each discovery or solution spawns numerous other questions, giving rising to a self-perpetuating cycle of inquiry. While science is not the sole route of acquiring meaning, history shows that scientific knowledge has been a powerful force for shaping the evolution of human societies.

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[49] Iaccarino, M., 2003. Science and culture: Western science could learn a thing or two from the way science is done in other cultures. EMBO reports, 4(3), pp.220-223.

[50] How Early Islamic Science Advanced Medicine

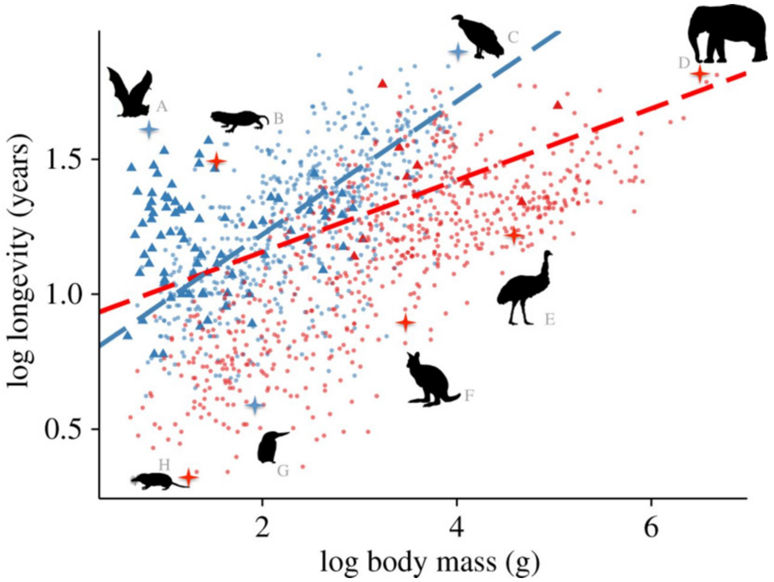
[51] Marvels of creates and strange things existing.

Appendix

Activity 1: inductive and deductive reasoning — Correlation between body mass and lifespan in animals[52]

The following graph shows the relationship between body mass and lifespan in a variety of birds and mammals. After studying the graph, answer the questions that follow.

Note to teachers: the aim of this activity is for students to analyse their own thought processes when answering these questions. Do not focus on the biological concepts about body mass and longevity. The rule to observe is this: generalising = induction; deriving = deduction



The animals shown in this figure are (A) Brandt's bat; (B) naked mole rat; (C) Adean condor; (D) African elephant; (E) emu; (F) Papuan forest-wallaby; (G) pied kingfisher and (H) forest shrew. Blue points and line represent volant (capable of flying) birds and mammals. Red points and line represent non-volant birds and mammals. Blue triangles represent bat species and red triangles represent non-volant bird species. This figure was obtained from Kevin Healy et al. Proc. R. Soc. B 2014; 281:20140298

1. What is the relationship between body mass and longevity? Did you decide this by deduction or induction?
2. Generally, how does a flying vs. a non-flying lifestyle make a difference to the general relationship between body mass and longevity? Did you decide this by deduction or induction?
3. Mark on your graph where you estimate the following animals would appear (you may need additional information from the internet):
    a. Grizzly bear
    b. Mole
    c. Etruscan pygmy shrew (weighing only 1.3 grams)
    d. Pelican
    e. *Homo sapiens*

For each animal listed in question 3, did you use deductive or inductive reasoning, or a combination of both? Do you think any of your data points is anomalous? Explain.

Consider the following statement: All living things are made up of cells. Explain how you can arrive at this conclusion through inductive thinking. Explain how you can arrive at this conclusion through deductive thinking.

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[52] Adapted from Ways of knowing.

Activity 2: Inductive reasoning – cell division[53]

During cell division, a parental cell divides to form two daughter cells. In eukaryotic cells, the process of cell division is referred to as mitosis. There are five distinct stages of mitosis – prophase, metaphase, anaphase and telophase. A cell that is not dividing is said to be in interphase. A scientist was examining cell division in the roots of a plant. He observed that cells of the roots were in different stages of mitosis or in interphase. His data is shown in the table below.

Sample	Interphase	Prophase	Metaphase	Anaphase	Telophase
1	45	15	5	3	5
2	89	23	5	4	9
3	101	17	6	2	8
4	67	27	3	1	7
5	88	34	6	0	8
6	77	33	3	2	5
7	89	24	5	3	7
8	45	12	3	3	3
9	68	12	4	5	6

This table shows the data collected by the scientist. For each sample, the numbers of cells in the different stages of mitosis or interphase was recorded.

1. Develop as many hypotheses as you can from the data provided.
2. Explain why deriving hypotheses is an example of inductive reasoning.

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[53] Adapted from Mitosis, accessed 22 October 2018

Activity 3: falsifiability[54]

For each of the following sets of statements, select the statement that is falsifiable

1. Set 1
    a. There is intelligent life on other stars.
    b. The Moon is made entirely of cheese.
    c. Isaac Newton was the greatest scientist.
    d. There is beauty in the sunset.
    e. There is cheese on the Moon.
1. Set 2
    a. The Minoans were the first civilisation on Crete.
    b. The Minoans were the best civilisation on Crete.
    c. The Minoans were not the first civilisation on Crete.
    d. The Minoans were not the best civilisation on Crete.
    e. The Minoans were a civilisation on Crete.
2. Set 3
    a. Passenger pigeons are extinct.
    b. Passenger pigeons are not extinct.
    c. Passenger pigeons taste good.
    d. Passenger pigeons taste terrible.
    e. Passenger pigeons were pests.
3. Set 4
    a. There is fish in Lake Nyak.
    b. All of the fish in Lake Nyak is green.
    c. All of the fish in Lake Nyak is beautiful.
4. Set 5
    a. There is no green fish in Lake Nyak.
    b. All of the fish in Lake Nyak is ugly.
    c. There is green fish in Lake Nyak.

What general conclusion can you make about the falsifiability of propositions?

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[54] https://courses.vcu.edu/PHY-rhg/astron/html/mod/006/t1/qst.html;

Falsifiability - answers

Answers are shown in bold.

1. Set 1
    a. (A) There is intelligent life on other stars.
    b. (B) **The Moon is made entirely of cheese.** (All you need to falsify the statement is a single moon-rock that is not made of cheese.)
    c. (C) Isaac Newton was the greatest scientist.
    d. (D) There is beauty in the sunset.
    e. (E) There is cheese on the Moon.
5. Set 2
    a. (A) **The Minoans were the first civilisation on Crete.** Just one pot that is from an earlier civilisation on Crete will falsify the statement.
    b. (B) The Minoans were the best civilisation on Crete.
    c. (C) The Minoans were not the first civilisation on Crete.
    d. (D) The Minoans were not the best civilisation on Crete.
    e. (E) The Minoans were a civilisation on Crete.
6. Set 3
    a. (A) **Passenger pigeons are extinct.** (Just one live passenger pigeon will falsify the statement.)
    b. (B) Passenger pigeons are not extinct.
    c. (C) Passenger pigeons taste good.
    d. (D) Passenger pigeons taste terrible.
    e. (E) Passenger pigeons were pests.
7. Set 4
    a. (A) There is fish in Lake Nyak.
    b. (B) **All of the fish in Lake Nyak is green.** (Finding just one red (or brown or pink) fish would falsify the statement.)
    c. (C) All of the fish in Lake Nyak is beautiful.
8. Set 5
    a. (A) **There are no green fish in Lake Nyak.** (Finding just one green fish would falsify the statement.)
    b. (B) All of the fish in Lake Nyak is ugly.
    c. (C) There is green fish in Lake Nyak.

Statements that are based on aesthetics, values, moral and ethical judgements are difficult to falsify. Some propositions are falsifiable, but cannot be practically investigated. For example, in Set 1, the statement ‘there is no cheese on the moon’ can be falsified, but one may have to spend an extraordinarily long time in search of the lunar cheese! In science, such propositions are not considered to be worth investigating (considering the time, and financial constraints on scientific investigations).