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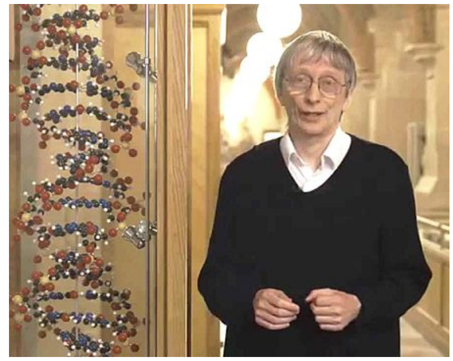
# Scientific method

The **scientific method** is an empirical method of acquiring knowledge that has characterized the development of science since at least the 17th century. It involves careful observation, applying rigorous skepticism about what is observed, given that cognitive assumptions can distort how one interprets the observation. It involves formulating hypotheses, via induction, based on such observations; experimental and measurement-based testing of deductions drawn from the hypotheses; and refinement (or elimination) of the hypotheses based on the experimental findings. These are *principles* of the scientific method, as distinguished from a definitive series of steps applicable to all scientific enterprises.[1][2][3]


Model of DNA with David Deutsch, proponent of invariant scientific explanations. See § DNA example below.

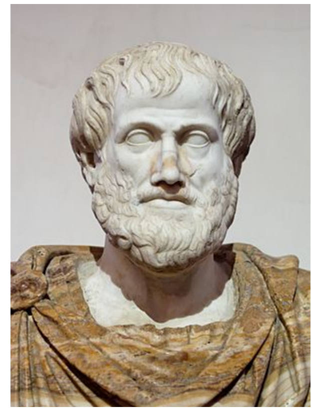
Though diverse models for the scientific method are available, there is in general a continuous **process** that includes observations about the natural world. People are naturally inquisitive, so they often come up with questions about things they see or hear, and they often develop ideas or hypotheses about why things are the way they are. The best hypotheses lead to predictions that can be tested in various ways. The most conclusive testing of hypotheses comes from reasoning based on carefully controlled experimental data. Depending on how well additional tests match the predictions, the original hypothesis may require refinement, alteration, expansion or even rejection. If a particular hypothesis becomes very well supported, a general theory may be developed.[4]

Although procedures vary from one field of inquiry to another, they are frequently the same from one to another. The process of the scientific method involves making conjectures (hypotheses), deriving predictions from them as logical consequences, and then carrying out experiments or empirical observations based on those predictions.[5][6] A hypothesis is a conjecture, based on knowledge obtained while seeking answers to the question. The hypothesis might be very specific, or it might be broad. Scientists then test hypotheses by conducting experiments or studies. A scientific hypothesis must be falsifiable, implying that it is possible to identify a possible outcome of an experiment or observation that conflicts with predictions deduced from the hypothesis; otherwise, the hypothesis cannot be meaningfully tested.[7]

The purpose of an experiment is to determine whether observations agree with or conflict with the predictions derived from a hypothesis.[8] Experiments can take place anywhere from a garage to CERN's Large Hadron Collider. There are difficulties in a formulaic statement of method, however. Though the scientific method is often presented as a fixed sequence of steps, it represents rather a set of general principles.[9] Not all steps take place in every scientific inquiry (nor to the same degree), and they are not always in the same order.[10][11]

## Contents

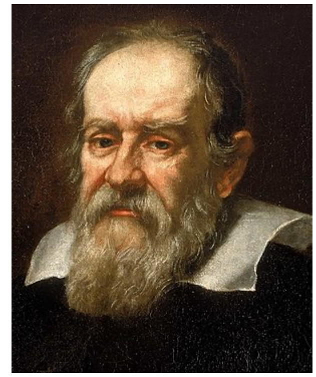
# History



Aristotle, 384–322 BCE. "As regards his method, Aristotle is recognized as the inventor of scientific method because of his refined analysis of logical implications contained in demonstrative discourse, which goes well beyond natural logic and does not owe anything to the ones who philosophized before him." – Riccardo Pozzo[12]

Ibn al-Haytham (Alhazen), 965–1039 Iraq. A polymath, considered by some to be the father of modern scientific methodology, due to his emphasis on experimental data and reproducibility of its results.[13][14]

Johannes Kepler (1571–1630). "Kepler shows his keen logical sense in detailing the whole process by which he finally arrived at the true orbit. This is the greatest piece of Retroductive reasoning ever performed." – C. S. Peirce, c. 1896, on Kepler's reasoning through explanatory hypotheses[15]



Galileo Galilei (1564–1642). According to Albert Einstein, "All knowledge of reality starts from experience and ends in it. Propositions arrived at by purely logical means are completely empty as regards reality. Because Galileo saw this, and particularly because he drummed it into the scientific world, he is the father of modern physics – indeed, of modern science altogether."[16]

Important debates in the history of science concern rationalism, especially as advocated by René Descartes; inductivism and/or empiricism, as argued for by Francis Bacon, and rising to particular prominence with Isaac Newton and his followers; and hypothetico-deductivism, which came to the fore in the early 19th century.

The term "scientific method" emerged in the 19th century, when a significant institutional development of science was taking place and terminologies establishing clear boundaries between science and non-science, such as "scientist" and "pseudoscience", appeared.[17] Throughout the 1830s and 1850s, by which time Baconianism was popular, naturalists like William Whewell, John Herschel, John Stuart Mill engaged in debates over "induction" and "facts" and were focused on how to generate knowledge.[17] In the late 19th and early 20th centuries, a debate over realism vs. antirealism was conducted as powerful scientific theories extended beyond the realm of the observable.[18]

The term "scientific method" came into popular use in the twentieth century, popping up in dictionaries and science textbooks, although there was little scientific consensus over its meaning.[17] Although there was a growth through the middle of the twentieth century, by the 1960s and 1970s numerous influential philosophers of science such as Thomas Kuhn and Paul Feyerabend had questioned the universality of the "scientific method" and in doing so largely replaced the notion of science as a homogeneous and universal method with that of it being a heterogeneous and local practice.[17] In particular, Paul Feyerabend, in the 1975 first edition of his book *Against Method*, argued against there being any universal rules of science.[18] Later examples include physicist Lee Smolin's 2013 essay "There Is No Scientific Method"[19] and historian of science Daniel Thurs's 2015 book *Newton's Apple and Other*

*Myths about Science*, which concluded that the scientific method is a myth or, at best, an idealization.[20] Philosophers Robert Nola and Howard Sankey, in their 2007 book *Theories of Scientific Method*, said that debates over scientific method continue, and argued that Feyerabend, despite the title of *Against Method*, accepted certain rules of method and attempted to justify those rules with a metamethodology.[21]

# Overview

The scientific method is the process by which science is carried out.[22] As in other areas of inquiry, science (through the scientific method) can build on previous knowledge and develop a more sophisticated understanding of its topics of study over time.[23][24][25][26][27][28] This model can be seen to underlie the scientific revolution.[29]

The ubiquitous element in scientific method is empiricism. This is in opposition to stringent forms of rationalism: the scientific method embodies that reason alone cannot solve a particular scientific problem. A strong formulation of the scientific method is not always aligned with a form of empiricism in which the empirical data is put forward in the form of experience or other abstracted forms of knowledge; in current scientific practice, however, the use of scientific modelling and reliance on abstract typologies and theories is normally accepted. The scientific method is of necessity also an expression of an opposition to claims that e.g. revelation, political or religious dogma, appeals to tradition, commonly held beliefs, common sense, or, importantly, currently held theories, are the only possible means of demonstrating truth.

Different early expressions of empiricism and the scientific method can be found throughout history, for instance with the ancient Stoics, Epicurus,[30] Alhazen,[31] Roger Bacon, and William of Ockham. From the 16th century onwards, experiments were advocated by Francis Bacon, and performed by Giambattista della Porta,[32] Johannes Kepler,[33] and Galileo Galilei.[34] There was particular development aided by theoretical works by Francisco Sanches,[35] John Locke, George Berkeley, and David Hume.

The hypothetico-deductive model[36] formulated in the 20th century, is the ideal although it has undergone significant revision since first proposed (for a more formal discussion, see below). Staddon (2017) argues it is a mistake to try following rules[37] which are best learned through careful study of examples of scientific investigation.

## Process

The overall process involves making conjectures (hypotheses), deriving predictions from them as logical consequences, and then carrying out experiments based on those predictions to determine whether the original conjecture was correct.[5] There are difficulties in a formulaic statement of method, however. Though the scientific method is often presented as a fixed sequence of steps, these actions are better considered as general principles.[10] Not all steps take place in every scientific inquiry (nor to the same degree), and they are not always done in the same order. As noted by scientist and philosopher William Whewell (1794–1866), "invention, sagacity, [and] genius"[11] are required at every step.

### Formulation of a question

The question can refer to the explanation of a specific observation, as in "Why is the sky blue?" but can also be open-ended, as in "How can I design a drug to cure this particular disease?" This stage frequently involves finding and evaluating evidence from previous experiments, personal scientific observations or assertions, as well as the work of other scientists. If the answer is already known, a different question that builds on the evidence can be posed. When applying the scientific method to research, determining a good question can be very difficult and it will affect the outcome of the investigation.[38]

### Hypothesis

A hypothesis is a conjecture, based on knowledge obtained while formulating the question, that may explain any given behavior. The hypothesis might be very specific; for example, Einstein's equivalence principle or Francis Crick's "DNA makes RNA makes protein",[39] or it might be broad; for example, unknown species of life dwell in the unexplored depths of the oceans. A statistical hypothesis is a conjecture about a given statistical population. For example, the population might be *people with a particular disease*. The conjecture might be that a new drug will cure the disease in some of those people. Terms commonly associated with statistical hypotheses are null hypothesis and alternative hypothesis. A null hypothesis is the conjecture that the statistical hypothesis is false; for example, that the new drug does nothing and that any cure is caused by chance. Researchers normally want to show that the null hypothesis is false. The alternative hypothesis is the desired outcome, that the drug does better than chance. A final point: a scientific hypothesis must be falsifiable, meaning that one can identify a possible outcome of an experiment that conflicts with predictions deduced from the hypothesis; otherwise, it cannot be meaningfully tested.

### Prediction

This step involves determining the logical consequences of the hypothesis. One or more predictions are then selected for further testing. The more unlikely that a prediction would be correct simply by coincidence, then the more convincing it would be if the prediction were fulfilled; evidence is also stronger if the answer to the prediction is not already known, due to the effects of hindsight bias (see also postdiction). Ideally, the prediction must also distinguish the hypothesis from likely alternatives; if two hypotheses make the same prediction, observing the prediction to be correct is not evidence for either one over the other. (These statements about the relative strength of evidence can be mathematically derived using Bayes' Theorem).[40]

### Testing

This is an investigation of whether the real world behaves as predicted by the hypothesis. Scientists (and other people) test hypotheses by conducting experiments. The purpose of an experiment is to determine whether observations of the real world agree with or conflict with the predictions derived from a hypothesis. If they agree, confidence in the hypothesis increases; otherwise, it decreases. Agreement does not assure that the hypothesis is true; future experiments may reveal problems. Karl Popper advised scientists to try to falsify hypotheses, i.e., to search for and test those experiments that seem most doubtful. Large numbers of successful confirmations are not convincing if they arise from experiments that avoid risk.[8] Experiments should be designed to minimize possible errors, especially through the use of appropriate scientific controls. For example, tests of medical treatments are commonly run as double-blind tests. Test personnel, who might unwittingly reveal to test subjects which samples are the desired test drugs and which are placebos, are kept ignorant of which are which. Such hints can bias the responses of the test subjects. Furthermore, failure of an experiment does not necessarily mean the hypothesis is false. Experiments always depend on several hypotheses, e.g., that the test equipment is working properly, and a failure may be a failure of one of the auxiliary hypotheses. (See the Duhem–Quine thesis.) Experiments can be conducted in a college lab, on a kitchen table, at CERN's Large Hadron Collider, at the bottom of an ocean, on Mars (using one of the working rovers), and so on. Astronomers do experiments, searching for planets around distant stars. Finally, most individual experiments address highly specific topics for reasons of practicality. As a result, evidence about broader topics is usually accumulated gradually.

### Analysis

This involves determining what the results of the experiment show and deciding on the next actions to take. The predictions of the hypothesis are compared to those of the null hypothesis, to determine which is better able to explain the data. In cases where an experiment is repeated many times, a statistical analysis such as a chi-squared test may be required. If the evidence has falsified the hypothesis, a new hypothesis is required; if the experiment supports the hypothesis but the evidence is not strong enough for high confidence, other predictions from the hypothesis must be tested. Once a hypothesis is strongly supported by evidence, a new question can be asked to provide further insight on the same topic. Evidence from other scientists and experience are frequently incorporated at any stage in the process. Depending on the complexity of the experiment, many iterations may be required to gather sufficient evidence to answer a question with confidence or to build up many answers to highly specific questions in order to answer a single broader question.

## DNA example

The basic elements of the scientific method are illustrated by the following example from the discovery of the structure of DNA:

- *Question*: Previous investigation of DNA had determined its chemical composition (the four nucleotides), the structure of each individual nucleotide, and other properties. It had been identified as the carrier of genetic information by the Avery–MacLeod–McCarty experiment in 1944,[41] but the mechanism of how genetic information was stored in DNA was unclear.
- *Hypothesis*: Linus Pauling, Francis Crick and James D. Watson hypothesized that DNA had a helical structure.[42]
- *Prediction*: If DNA had a helical structure, its X-ray diffraction pattern would be X-shaped.[43][44] This prediction was determined using the mathematics of the helix transform, which had been derived by Cochran, Crick and Vand[45] (and independently by Stokes). This prediction was a mathematical construct, completely independent from the biological problem at hand.
- *Experiment*: Rosalind Franklin crystallized pure DNA and performed X-ray diffraction to produce photo 51. The results showed an X-shape.
- *Analysis*: When Watson saw the detailed diffraction pattern, he immediately recognized it as a helix.[46][47] He and Crick then produced their model, using this information along with the previously known information about DNA's composition and about molecular interactions such as hydrogen bonds.[48]

The discovery became the starting point for many further studies involving the genetic material, such as the field of molecular genetics, and it was awarded the Nobel Prize in 1962. Each step of the example is examined in more detail later in the article.

## Other components

The scientific method also includes other components required even when all the iterations of the steps above have been completed:[49]

#### Replication

If an experiment cannot be repeated to produce the same results, this implies that the original results might have been in error. As a result, it is common for a single experiment to be performed multiple times, especially when there are uncontrolled variables or other indications of experimental error. For significant or surprising results, other scientists may also attempt to replicate the results for themselves, especially if those results would be important to their own work.[50] Replication has become a contentious issue in social and biomedical science where treatments are administered to groups of individuals. Typically an *experimental group* gets the treatment, such as drug, and the *control group* gets a placebo. John Ioannidis in 2005 pointed out that the method being used has led to many findings that cannot be replicated.[51]

#### External review

The process of peer review involves evaluation of the experiment by experts, who typically give their opinions anonymously. Some journals request that the experimenter provide lists of possible peer reviewers, especially if the field is highly specialized. Peer-review does not certify the correctness of the results, only that, in the opinion of the reviewer, the experiments themselves were sound (based on the description supplied by the experimenter). If the work passes peer review, which occasionally may require new experiments requested by the reviewers, it will be published in a peer-reviewed scientific journal. The specific journal that publishes the results indicates the perceived quality of the work.[52]

#### Data recording and sharing

Scientists typically are careful in recording their data, a requirement promoted by Ludwik Fleck (1896–1961) and others.[53] Though not typically required, they might be requested to supply this data to other scientists who wish to replicate their original results (or parts of their original results), extending to the sharing of any experimental samples that may be difficult to obtain.[54]

## Scientific inquiry

Scientific inquiry generally aims to obtain knowledge in the form of testable explanations that scientists can use to predict the results of future experiments. This allows scientists to gain a better understanding of the topic under study, and later to use that understanding to intervene in its causal mechanisms (such as to cure disease). The better an explanation is at making predictions, the more useful it frequently can be, and the more likely it will continue to explain a body of evidence better than its alternatives. The most successful explanations – those which explain and make accurate predictions in a wide range of circumstances – are often called scientific theories.

Most experimental results do not produce large changes in human understanding; improvements in theoretical scientific understanding typically result from a gradual process of development over time, sometimes across different domains of science.[55] Scientific models vary in the extent to which they have been experimentally tested and for how long, and in their acceptance in the scientific community. In general, explanations become accepted over time as evidence accumulates on a given topic, and the explanation in question proves more powerful than its alternatives at explaining the evidence. Often subsequent researchers re-formulate the explanations over time, or combined explanations to produce new explanations.

Tow sees the scientific method in terms of an evolutionary algorithm applied to science and technology.[56]

## Properties of scientific inquiry

Scientific knowledge is closely tied to empirical findings and can remain subject to falsification if new experimental observations are incompatible with what is found. That is, no theory can ever be considered final since new problematic evidence might be discovered. If such evidence is found, a new theory may be proposed, or (more commonly) it is found that modifications to the previous theory are sufficient to explain the new evidence. The strength of a theory can be argued to relate to how long it has persisted without major alteration to its core principles.

Theories can also become subsumed by other theories. For example, Newton's laws explained thousands of years of scientific observations of the planets almost perfectly. However, these laws were then determined to be special cases of a more general theory (relativity), which explained both the (previously unexplained) exceptions to Newton's laws and predicted and explained other observations such as the deflection of light by gravity. Thus, in certain cases independent, unconnected, scientific observations can be connected to each other, unified by principles of increasing explanatory power.[57][58]

Since new theories might be more comprehensive than what preceded them, and thus be able to explain more than previous ones, successor theories might be able to meet a higher standard by explaining a larger body of observations than their predecessors.[57] For example, the theory of evolution explains the diversity of life on Earth, how species adapt to their environments, and many other patterns observed in the natural world;[59][60] its most recent major modification was unification with genetics to form the modern evolutionary synthesis. In subsequent modifications, it has also subsumed aspects of many other fields such as biochemistry and molecular biology.

## Beliefs and biases

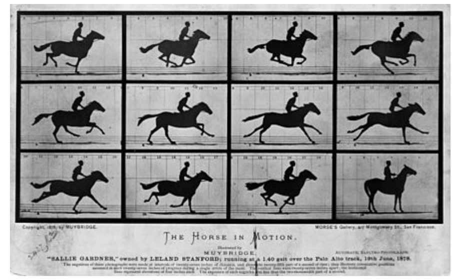
Scientific methodology often directs that hypotheses be tested in controlled conditions wherever possible. This is frequently possible in certain areas, such as in the biological sciences, and more difficult in other areas, such as in astronomy.

The practice of experimental control and reproducibility can have the effect of diminishing the potentially harmful effects of circumstance, and to a degree, personal bias. For example, pre-existing beliefs can alter the interpretation of results, as in confirmation bias; this is a heuristic that leads a person with a particular belief to see things as reinforcing their belief, even if another observer might disagree (in other words, people tend to observe what they expect to observe).

A historical example is the belief that the legs of a galloping horse are splayed at the point when none of the horse's legs touch the ground, to the point of this image being included in paintings by its supporters. However, the first stop-action pictures of a horse's gallop by Eadweard Muybridge showed this to be false, and that the legs are instead gathered together.[61]

Another important human bias that plays a role is a preference for new, surprising statements (see appeal to novelty), which can result in a search for evidence that the new is true.[62] Poorly attested beliefs can be believed and acted upon via a less rigorous heuristic.[63]

Flying gallop as shown by this painting (Théodore Géricault, 1821) is falsified; see below.




Muybridge's photographs of *The Horse in Motion*, 1878, were used to answer the question of whether all four feet of a galloping horse are ever off the ground at the same time. This demonstrates a use of photography as an experimental tool in science.

Goldhaber and Nieto published in 2010 the observation that if theoretical structures with "many closely neighboring subjects are described by connecting theoretical concepts, then the theoretical structure acquires a robustness which makes it increasingly hard—though certainly never impossible—to overturn".[58] When a narrative is constructed its elements become easier to believe.[64] For more on the narrative fallacy, see also Fleck 1979, p. 27: "Words and ideas are originally phonetic and mental equivalences of the experiences coinciding with them. ... Such proto-ideas are at first always too broad and insufficiently specialized. ... Once a structurally complete and closed system of opinions consisting of many details and relations has been formed, it offers enduring resistance to anything that contradicts it." Sometimes, these have their elements assumed *a priori*, or contain some other logical or methodological flaw in the process that ultimately produced them. Donald M. MacKay has analyzed these elements in terms of limits to the accuracy of measurement and has related them to instrumental elements in a category of measurement.[65]

# Elements of the scientific method

There are different ways of outlining the basic method used for scientific inquiry. The scientific community and philosophers of science generally agree on the following classification of method components. These methodological elements and organization of procedures tend to be more characteristic of natural sciences than social sciences. Nonetheless, the cycle of formulating hypotheses, testing and analyzing the results, and formulating new hypotheses, will resemble the cycle described below.

The scientific method is an iterative, cyclical process through which information is continually revised.[66][67] It is generally recognized to develop advances in knowledge through the following elements, in varying combinations or contributions:[68][69]

- Characterizations (observations, definitions, and measurements of the subject of inquiry)
- Hypotheses (theoretical, hypothetical explanations of observations and measurements of the subject)
- Predictions (inductive and deductive reasoning from the hypothesis or theory)
- Experiments (tests of all of the above)

Each element of the scientific method is subject to peer review for possible mistakes. These activities do not describe all that scientists do (see below) but apply mostly to experimental sciences (e.g., physics, chemistry, and biology). The elements above are often taught in the educational system as "the scientific method".[70]

The scientific method is not a single recipe: it requires intelligence, imagination, and creativity.[71] In this sense, it is not a mindless set of standards and procedures to follow, but is rather an ongoing cycle, constantly developing more useful, accurate and comprehensive models and methods. For example, when Einstein developed the Special and General Theories of Relativity, he did not in any way refute or discount Newton's *Principia*. On the contrary, if the astronomically massive, the feather-light, and the extremely fast are removed from Einstein's theories – all phenomena Newton could not have observed – Newton's equations are what remain. Einstein's theories are expansions and refinements of Newton's theories and, thus, increase confidence in Newton's work.

A linearized, pragmatic scheme of the four points above is sometimes offered as a guideline for proceeding:[72]

1. Define a question
2. Gather information and resources (observe)
3. Form an explanatory hypothesis
4. Test the hypothesis by performing an experiment and collecting data in a reproducible manner
5. Analyze the data
6. Interpret the data and draw conclusions that serve as a starting point for new hypothesis
7. Publish results
8. Retest (frequently done by other scientists)

The iterative cycle inherent in this step-by-step method goes from point 3 to 6 back to 3 again.

While this schema outlines a typical hypothesis/testing method,[73] a number of philosophers, historians, and sociologists of science, including Paul Feyerabend, claim that such descriptions of scientific method have little relation to the ways that science is actually practiced.

## Characterizations

The scientific method depends upon increasingly sophisticated characterizations of the subjects of investigation. (The *subjects* can also be called *unsolved problems* or the *unknowns*.) For example, Benjamin Franklin conjectured, correctly, that St. Elmo's fire was electrical in nature, but it has taken a long series of experiments and theoretical changes to establish this. While seeking the pertinent properties of the subjects, careful thought may also entail some definitions and observations; the observations often demand careful measurements and/or counting.

The systematic, careful collection of measurements or counts of relevant quantities is often the critical difference between pseudo-sciences, such as alchemy, and science, such as chemistry or biology. Scientific measurements are usually tabulated, graphed, or mapped, and statistical manipulations, such as correlation and regression, performed on them. The measurements might be made in a controlled setting, such as a laboratory, or made on more or less inaccessible or unmanipulatable objects such as stars or human populations. The measurements often require specialized scientific instruments such as thermometers, spectroscopes, particle accelerators, or voltmeters, and the progress of a scientific field is usually intimately tied to their invention and improvement.

> I am not accustomed to saying anything with certainty after only one or two observations.
>
> — Andreas Vesalius, (1546)[74]

### Uncertainty

Measurements in scientific work are also usually accompanied by estimates of their uncertainty. The uncertainty is often estimated by making repeated measurements of the desired quantity. Uncertainties may also be calculated by consideration of the uncertainties of the individual underlying quantities used. Counts of things, such as the number of people in a nation at a particular time, may also have an uncertainty due to data collection limitations. Or counts may represent a sample of desired quantities, with an uncertainty that depends upon the sampling method used and the number of samples taken.

### Definition

Measurements demand the use of *operational definitions* of relevant quantities. That is, a scientific quantity is described or defined by how it is measured, as opposed to some more vague, inexact or "idealized" definition. For example, electric current, measured in amperes, may be operationally defined in terms of the mass of silver deposited in a certain time on an electrode in an electrochemical device that is described in some detail. The operational definition of a thing often relies on comparisons with standards: the operational definition of "mass" ultimately relies on the use of an artifact, such as a particular kilogram of platinum-iridium kept in a laboratory in France.

The scientific definition of a term sometimes differs substantially from its natural language usage. For example, mass and weight overlap in meaning in common discourse, but have distinct meanings in mechanics. Scientific quantities are often characterized by their units of measure which can later be described in terms of conventional physical units when communicating the work.

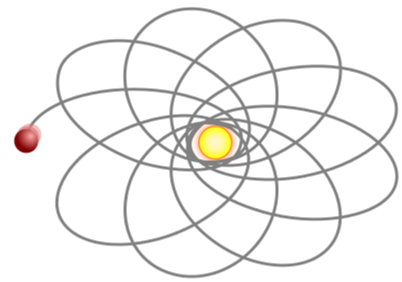
New theories are sometimes developed after realizing certain terms have not previously been sufficiently clearly defined. For example, Albert Einstein's first paper on relativity begins by defining simultaneity and the means for determining length. These ideas were skipped over by Isaac Newton with, "I do not define time, space, place and motion, as being well known to all." Einstein's paper then demonstrates that they (viz., absolute time and length independent of motion) were approximations. Francis Crick cautions us that when characterizing a subject, however, it can be premature to define something when it remains ill-understood.[75] In Crick's study of consciousness, he actually found it easier to study awareness in the visual system, rather than to study free will, for example. His cautionary example was the gene; the gene was much more poorly understood before Watson and Crick's pioneering discovery of the structure of DNA; it would have been counterproductive to spend much time on the definition of the gene, before them.

### DNA-characterizations

The history of the discovery of the structure of DNA is a classic example of the elements of the scientific method: in 1950 it was known that genetic inheritance had a mathematical description, starting with the studies of Gregor Mendel, and that DNA contained genetic information (Oswald Avery's *transforming principle*).[41] But the mechanism of storing genetic information (i.e., genes) in DNA was unclear. Researchers in Bragg's laboratory at Cambridge University made X-ray diffraction pictures of various molecules, starting with crystals of salt, and proceeding to more complicated substances. Using clues painstakingly assembled over decades, beginning with its chemical composition, it was determined that it should be possible to characterize the physical structure of DNA, and the X-ray images would be the vehicle.[76] *..2. DNA-hypotheses*

### Another example: precession of Mercury

The characterization element can require extended and extensive study, even centuries. It took thousands of years of measurements, from the Chaldean, Indian, Persian, Greek, Arabic and European astronomers, to fully record the motion of planet Earth. Newton was able to include those measurements into consequences of his laws of motion. But the perihelion of the planet Mercury's orbit exhibits a precession that cannot be fully explained by Newton's laws of motion (see diagram to the right), as Leverrier pointed out in 1859. The observed difference for Mercury's precession between Newtonian theory and observation was one of the things that occurred to Albert Einstein as a possible early test of his theory of General relativity. His relativistic calculations matched observation much more closely than did Newtonian theory. The difference is approximately 43 arc-seconds per century.



Precession of the perihelion — exaggerated in the case of Mercury, but observed in the case of S2's apsidal precession around Sagittarius A*[77]

## Hypothesis development

A hypothesis is a suggested explanation of a phenomenon, or alternately a reasoned proposal suggesting a possible correlation between or among a set of phenomena.

Normally hypotheses have the form of a mathematical model. Sometimes, but not always, they can also be formulated as existential statements, stating that some particular instance of the phenomenon being studied has some characteristic and causal explanations, which have the general form of universal statements, stating that every instance of the phenomenon has a particular characteristic.

Scientists are free to use whatever resources they have – their own creativity, ideas from other fields, inductive reasoning, Bayesian inference, and so on – to imagine possible explanations for a phenomenon under study. Albert Einstein once observed that "there is no logical bridge between phenomena and their theoretical principles."[78] Charles Sanders Peirce, borrowing a page from Aristotle (*Prior Analytics*, 2.25) described the incipient stages of inquiry, instigated by the "irritation of doubt" to venture a plausible guess, as *abductive reasoning*. The history of science is filled with stories of scientists claiming a "flash of inspiration", or a hunch, which then motivated them to look for evidence to support or refute their idea. Michael Polanyi made such creativity the centerpiece of his discussion of methodology.

William Glen observes that[79]

> the success of a hypothesis, or its service to science, lies not simply in its perceived "truth", or power to displace, subsume or reduce a predecessor idea, but perhaps more in its ability to stimulate the research that will illuminate ... bald suppositions and areas of vagueness.

In general scientists tend to look for theories that are "elegant" or "beautiful". Scientists often use these terms to refer to a theory that is in accordance with the known facts, but is nevertheless relatively simple and easy to handle. Occam's Razor serves as a rule of thumb for choosing the most desirable amongst a group of equally explanatory hypotheses.

To minimize the confirmation bias which results from entertaining a single hypothesis, strong inference emphasizes the need for entertaining multiple alternative hypotheses.[80]

### DNA-hypotheses

Linus Pauling proposed that DNA might be a triple helix.[81] This hypothesis was also considered by Francis Crick and James D. Watson but discarded. When Watson and Crick learned of Pauling's hypothesis, they understood from existing data that Pauling was wrong[82] and that Pauling would soon admit his difficulties with that structure. So, the race was on to figure out the correct structure (except that Pauling did not realize at the time that he was in a race) *..3. DNA-predictions*

## Predictions from the hypothesis

Any useful hypothesis will enable predictions, by reasoning including deductive reasoning. It might predict the outcome of an experiment in a laboratory setting or the observation of a phenomenon in nature. The prediction can also be statistical and deal only with probabilities.

It is essential that the outcome of testing such a prediction be currently unknown. Only in this case does a successful outcome increase the probability that the hypothesis is true. If the outcome is already known, it is called a consequence and should have already been considered while formulating the hypothesis.

If the predictions are not accessible by observation or experience, the hypothesis is not yet testable and so will remain to that extent unscientific in a strict sense. A new technology or theory might make the necessary experiments feasible. For example, while a hypothesis on the existence of other intelligent species may be convincing with scientifically based speculation, there is no known experiment that can test this hypothesis. Therefore, science itself can have little to say about the possibility. In the future, a new technique may allow for an experimental test and the speculation would then become part of accepted science.

### DNA-predictions

James D. Watson, Francis Crick, and others hypothesized that DNA had a helical structure. This implied that DNA's X-ray diffraction pattern would be 'x shaped'.[44][83] This prediction followed from the work of Cochran, Crick and Vand[45] (and independently by Stokes). The Cochran-Crick-Vand-Stokes theorem provided a mathematical explanation for the empirical observation that diffraction from helical structures produces x shaped patterns.

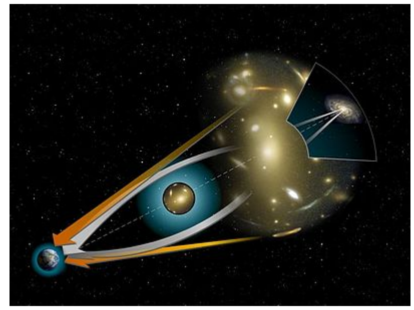
In their first paper, Watson and Crick also noted that the double helix structure they proposed provided a simple mechanism for DNA replication, writing, "It has not escaped our notice that the specific pairing we have postulated immediately suggests a possible copying mechanism for the genetic material".[84] *..4. DNA-experiments*

### Another example: general relativity

Einstein's theory of General Relativity makes several specific predictions about the observable structure of space-time, such as that light bends in a gravitational field, and that the amount of bending depends in a precise way on the strength of that gravitational field. Arthur Eddington's observations made during a 1919 solar eclipse supported General Relativity rather than Newtonian gravitation.[85]

## Experiments

Once predictions are made, they can be sought by experiments. If the test results contradict the predictions, the hypotheses which entailed them are called into question and become less tenable. Sometimes the experiments are conducted incorrectly or are not very well designed when compared to a crucial experiment. If the experimental results confirm the predictions, then the hypotheses are considered more likely to be correct, but might still be wrong and continue to be subject to further testing. The experimental control is a technique for dealing with observational error. This technique uses the contrast between multiple samples (or observations) under differing conditions to see what varies or what remains the same. We vary the conditions for each measurement, to help isolate what has changed. Mill's canons can then help us figure out what the important factor is.[86] Factor analysis is one technique for discovering the important factor in an effect.



Einstein's prediction (1907): Light bends in a gravitational field

Depending on the predictions, the experiments can have different shapes. It could be a classical experiment in a laboratory setting, a double-blind study or an archaeological excavation. Even taking a plane from New York to Paris is an experiment that tests the aerodynamical hypotheses used for constructing the plane.

Scientists assume an attitude of openness and accountability on the part of those conducting an experiment. Detailed record-keeping is essential, to aid in recording and reporting on the experimental results, and supports the effectiveness and integrity of the procedure. They will also assist in reproducing the experimental results, likely by others. Traces of this approach can be seen in the work of Hipparchus (190–120 BCE), when determining a value for the precession of the Earth, while controlled experiments can be seen in the works of Jābir ibn Hayyān (721–815 CE), al-Battani (853–929) and Alhazen (965–1039).[87]

#### DNA-experiments

Watson and Crick showed an initial (and incorrect) proposal for the structure of DNA to a team from Kings College – Rosalind Franklin, Maurice Wilkins, and Raymond Gosling. Franklin immediately spotted the flaws which concerned the water content. Later Watson saw Franklin's detailed X-ray diffraction images which showed an X-shape[88] and was able to confirm the structure was helical.[46][47] This rekindled Watson and Crick's model building and led to the correct structure. *..1. DNA-characterizations*

## Evaluation and improvement

The scientific method is iterative. At any stage, it is possible to refine its accuracy and precision, so that some consideration will lead the scientist to repeat an earlier part of the process. Failure to develop an interesting hypothesis may lead a scientist to re-define the subject under consideration. Failure of a hypothesis to produce interesting and testable predictions may lead to reconsideration of the hypothesis or of the definition of the subject. Failure of an experiment to produce interesting results may lead a scientist to reconsider the experimental method, the hypothesis, or the definition of the subject.

Other scientists may start their own research and enter the process at any stage. They might adopt the characterization and formulate their own hypothesis, or they might adopt the hypothesis and deduce their own predictions. Often the experiment is not done by the person who made the prediction, and the characterization is based on experiments done by someone else. Published results of experiments can also serve as a hypothesis predicting their own reproducibility.

#### DNA-iterations

After considerable fruitless experimentation, being discouraged by their superior from continuing, and numerous false starts,[89][90][91] Watson and Crick were able to infer the essential structure of DNA by concrete modeling of the physical shapes of the nucleotides which comprise it.[48][92] They were guided by the bond lengths which had been deduced by Linus Pauling and by Rosalind Franklin's X-ray diffraction images. *..DNA Example*

### Confirmation

Science is a social enterprise, and scientific work tends to be accepted by the scientific community when it has been confirmed. Crucially, experimental and theoretical results must be reproduced by others within the scientific community. Researchers have given their lives for this vision; Georg Wilhelm Richmann was killed by ball lightning (1753) when attempting to replicate the 1752 kite-flying experiment of Benjamin Franklin.[93]

To protect against bad science and fraudulent data, government research-granting agencies such as the National Science Foundation, and science journals, including *Nature* and *Science*, have a policy that researchers must archive their data and methods so that other researchers can test the data and methods and build on the research that has gone before. Scientific data archiving can be done at a number of national archives in the U.S. or in the World Data Center.

## Models of scientific inquiry

### Classical model

The classical model of scientific inquiry derives from Aristotle,[94] who distinguished the forms of approximate and exact reasoning, set out the threefold scheme of abductive, deductive, and inductive inference, and also treated the compound forms such as reasoning by analogy.

### Hypothetico-deductive model

The hypothetico-deductive model or method is a proposed description of scientific method. Here, predictions from the hypothesis are central: if you assume the hypothesis to be true, what consequences follow?

If subsequent empirical investigation does not demonstrate that these consequences or predictions correspond to the observable world, the hypothesis can be concluded to be false.

### Pragmatic model

In 1877,[23] Charles Sanders Peirce (1839–1914) characterized inquiry in general not as the pursuit of truth *per se* but as the struggle to move from irritating, inhibitory doubts born of surprises, disagreements, and the like, and to reach a secure belief, belief being that on which one is prepared to act. He framed scientific inquiry as part of a broader spectrum and as spurred, like inquiry generally, by actual doubt, not mere verbal or hyperbolic doubt, which he held to be fruitless.[95] He outlined four methods of settling opinion, ordered from least to most successful:

1. The method of tenacity (policy of sticking to initial belief) – which brings comforts and decisiveness but leads to trying to ignore contrary information and others' views as if truth were intrinsically private, not public. It goes against the social impulse and easily falters since one may well notice when another's opinion is as good as one's own initial opinion. Its successes can shine but tend to be transitory.[96]
2. The method of authority – which overcomes disagreements but sometimes brutally. Its successes can be majestic and long-lived, but it cannot operate thoroughly enough to suppress doubts indefinitely, especially when people learn of other societies present and past.
3. The method of the *a priori* – which promotes conformity less brutally but fosters opinions as something like tastes, arising in conversation and comparisons of perspectives in terms of "what is agreeable to reason." Thereby it depends on fashion in paradigms and goes in circles over time. It is more intellectual and respectable but, like the first two methods, sustains accidental and capricious beliefs, destining some minds to doubt it.
4. The scientific method – the method wherein inquiry regards itself as fallible and purposely tests itself and criticizes, corrects, and improves itself.

Peirce held that slow, stumbling ratiocination can be dangerously inferior to instinct and traditional sentiment in practical matters, and that the scientific method is best suited to theoretical research,[97] which in turn should not be trammeled by the other methods and practical ends; reason's "first rule" is that, in order to learn, one must desire to learn and, as a corollary, must not block the way of inquiry.[98] The scientific method excels the others by being deliberately designed to arrive – eventually – at the most secure beliefs, upon which the most successful practices can be based. Starting from the idea that people seek not truth *per se* but instead to subdue irritating, inhibitory doubt, Peirce showed how, through the struggle, some can come to submit to truth for the sake of belief's integrity, seek as truth the guidance of potential practice correctly to its given goal, and wed themselves to the scientific method.[23][26]

For Peirce, rational inquiry implies presuppositions about truth and the real; to reason is to presuppose (and at least to hope), as a principle of the reasoner's self-regulation, that the real is discoverable and independent of our vagaries of opinion. In that vein he defined truth as the correspondence of a sign (in particular, a proposition) to its object and, pragmatically, not as actual consensus of some definite, finite community (such that to inquire would be to poll the experts), but instead as that final opinion which all investigators *would* reach sooner or later but still inevitably, if they were to push investigation far enough, even when they start from different points.[99] In tandem he defined the real as a true sign's object (be that object a possibility or quality, or an actuality or brute fact, or a necessity or norm or law), which is what it is independently of any finite community's opinion and, pragmatically, depends only on the final opinion destined in a sufficient investigation. That is a destination as far, or near, as the truth itself to you or me or the given finite community. Thus, his theory of inquiry boils down to "Do the science." Those conceptions of truth and the real involve the idea of a community both without definite limits (and thus potentially self-correcting as far as needed) and capable of definite increase of knowledge.[100] As inference, "logic is rooted in the social principle" since it depends on a standpoint that is, in a sense, unlimited.[101]

Paying special attention to the generation of explanations, Peirce outlined the scientific method as a coordination of three kinds of inference in a purposeful cycle aimed at settling doubts, as follows (in §III–IV in "A Neglected Argument"[5] except as otherwise noted):

1. *Abduction* (or *retroduction*). Guessing, inference to explanatory hypotheses for selection of those best worth trying. From abduction, Peirce distinguishes induction as inferring, on the basis of tests, the proportion of truth in the hypothesis. Every inquiry, whether into ideas, brute facts, or norms and laws, arises from surprising observations in one or more of those realms (and for example at any stage of an inquiry already underway). All explanatory content of theories comes from abduction, which guesses a new or outside idea so as to account in a simple, economical way for a surprising or complicative phenomenon. Oftenest, even a well-prepared mind guesses wrong. But the modicum of success of our guesses far exceeds that of sheer luck and seems born of attunement to nature by instincts developed or inherent, especially insofar as best guesses are optimally plausible and simple in the sense, said Peirce, of the "facile and natural", as by Galileo's natural light of reason and as distinct from "logical simplicity". Abduction is the most fertile but least secure mode of inference. Its general rationale is inductive: it succeeds often enough and, without it, there is no hope of sufficiently expediting inquiry (often multi-generational) toward new truths.[102] Coordinative method leads from abducing a plausible hypothesis to judging it for its testability[103] and for how its trial would economize inquiry itself.[104] Peirce calls his pragmatism "the logic of abduction".[105] His pragmatic maxim is: "Consider what effects that might conceivably have practical bearings you conceive the objects of your conception to have. Then, your conception of those effects is the whole of your conception of the object".[99] His pragmatism is a method of reducing conceptual confusions fruitfully by equating the meaning of any conception with the conceivable practical implications of its object's conceived effects – a method of experimentational mental reflection hospitable to forming hypotheses and conducive to testing them. It favors efficiency. The hypothesis, being insecure, needs to have practical implications leading at least to mental tests and, in science, lending themselves to scientific tests. A simple but unlikely guess, if uncostly to test for falsity, may belong first in line for testing. A guess is intrinsically worth testing if it has instinctive plausibility or reasoned objective probability, while subjective likelihood, though reasoned, can be misleadingly seductive. Guesses can be chosen for trial strategically, for their caution (for which Peirce gave as an example the game of Twenty Questions), breadth, and incomplexity.[106] One can hope to discover only that which time would reveal through a learner's sufficient experience anyway, so the point is to expedite it; the economy of research is what demands the leap, so to speak, of abduction and governs its art.[104]
2. *Deduction*. Two stages:
   1. Explication. Unclearly premissed, but deductive, analysis of the hypothesis in order to render its parts as clear as possible.
   2. Demonstration: Deductive Argumentation, Euclidean in procedure. Explicit deduction of hypothesis's consequences as predictions, for induction to test, about evidence to be found. Corollarial or, if needed, theorematic.
3. *Induction*. The long-run validity of the rule of induction is deducible from the principle (presuppositional to reasoning in general[99]) that the real is only the object of the final opinion to which adequate investigation would lead;[107] anything to which no such process would ever lead would not be real. Induction involving ongoing tests or observations follows a method which, sufficiently persisted in, will diminish its error below any predesignate degree. Three stages:
   1. Classification. Unclearly premissed, but inductive, classing of objects of experience under general ideas.
   2. Probation: direct inductive argumentation. Crude (the enumeration of instances) or gradual (new estimate of proportion of truth in the hypothesis after each test). Gradual induction is qualitative or quantitative; if qualitative, then dependent on weightings of qualities or characters;[108] if quantitative, then dependent on measurements, or on statistics, or on countings.
   3. Sentential Induction. "...which, by inductive reasonings, appraises the different probations singly, then their combinations, then makes self-appraisal of these very appraisals themselves, and passes final judgment on the whole result".

# Science of complex systems

Science applied to complex systems can involve elements such as transdisciplinarity, systems theory and scientific modelling. The Santa Fe Institute studies such systems;[109] Murray Gell-Mann interconnects these topics with message passing.[110]

In general, the scientific method may be difficult to apply stringently to diverse, interconnected systems and large data sets. In particular, practices used within Big data, such as predictive analytics, may be considered to be at odds with the scientific method.[111]

# Communication and community

Frequently the scientific method is employed not only by a single person but also by several people cooperating directly or indirectly. Such cooperation can be regarded as an important element of a scientific community. Various standards of scientific methodology are used within such an environment.

## Peer review evaluation

Scientific journals use a process of *peer review*, in which scientists' manuscripts are submitted by editors of scientific journals to (usually one to three, and usually anonymous) fellow scientists familiar with the field for evaluation. In certain journals, the journal itself selects the referees; while in others (especially journals that are extremely specialized), the manuscript author might recommend referees. The referees may or may not recommend publication, or they might recommend publication with suggested modifications, or sometimes, publication in another journal. This standard is practiced to various degrees by different journals, and can have the effect of keeping the literature free of obvious errors and to generally improve the quality of the material, especially in the journals who use the standard most rigorously. The peer-review process can have limitations when considering research outside the conventional scientific paradigm: problems of "groupthink" can interfere with open and fair deliberation of some new research.[112]

## Documentation and replication

Sometimes experimenters may make systematic errors during their experiments, veer from standard methods and practices (Pathological science) for various reasons, or, in rare cases, deliberately report false results. Occasionally because of this then, other scientists might attempt to repeat the experiments in order to duplicate the results.

### Archiving

Researchers sometimes practice scientific data archiving, such as in compliance with the policies of government funding agencies and scientific journals. In these cases, detailed records of their experimental procedures, raw data, statistical analyses and source code can be preserved in order to provide evidence of the methodology and practice of the procedure and assist in any potential future attempts to reproduce the result. These procedural records may also assist in the conception of new experiments to test the hypothesis, and may prove useful to engineers who might examine the potential practical applications of a discovery.

### Data sharing

When additional information is needed before a study can be reproduced, the author of the study might be asked to provide it. They might provide it, or if the author refuses to share data, appeals can be made to the journal editors who published the study or to the institution which funded the research.

### Limitations

Since it is impossible for a scientist to record *everything* that took place in an experiment, facts selected for their apparent relevance are reported. This may lead, unavoidably, to problems later if some supposedly irrelevant feature is questioned. For example, Heinrich Hertz did not report the size of the room used to test Maxwell's equations, which later turned out to account for a small deviation in the results. The problem is that parts of the theory itself need to be assumed in order to select and report the experimental conditions. The observations are hence sometimes described as being 'theory-laden'.

# Philosophy and sociology of science

## Analytical philosophy

Philosophy of science looks at the underpinning logic of the scientific method, at what separates science from non-science, and the ethic that is implicit in science. There are basic assumptions, derived from philosophy by at least one prominent scientist, that form the base of the scientific method – namely, that reality is objective and consistent, that humans have the capacity to perceive reality accurately, and that rational explanations exist for elements of the real world.[113] These assumptions from methodological naturalism form a basis on which science may be grounded. Logical Positivist, empiricist, falsificationist, and other theories have criticized these assumptions and given alternative accounts of the logic of science, but each has also itself been criticized.

Thomas Kuhn examined the history of science in his *The Structure of Scientific Revolutions*, and found that the actual method used by scientists differed dramatically from the then-espoused method. His observations of science practice are essentially sociological and do not speak to how science is or can be practiced in other times and other cultures.

Norwood Russell Hanson, Imre Lakatos and Thomas Kuhn have done extensive work on the "theory-laden" character of observation. Hanson (1958) first coined the term for the idea that all observation is dependent on the conceptual framework of the observer, using the concept of gestalt to show how preconceptions can affect both observation and description.[114] He opens Chapter 1 with a discussion of the Golgi bodies and their initial rejection as an artefact of staining technique, and a discussion of Brahe and Kepler observing the dawn and seeing a "different" sun rise despite the same physiological phenomenon. Kuhn[115] and Feyerabend[116] acknowledge the pioneering significance of his work.

Kuhn (1961) said the scientist generally has a theory in mind before designing and undertaking experiments so as to make empirical observations, and that the "route from theory to measurement can almost never be traveled backward". This implies that the way in which theory is tested is dictated by the nature of the theory itself, which led Kuhn (1961, p. 166) to argue that "once it has been adopted by a profession ... no theory is recognized to be testable by any quantitative tests that it has not already passed".[117]

### Post-modernism and science wars

Paul Feyerabend similarly examined the history of science, and was led to deny that science is genuinely a methodological process. In his book *Against Method* he argues that scientific progress is *not* the result of applying any particular method. In essence, he says that for any specific method or norm of science, one can find a historic episode where violating it has contributed to the progress of science. Thus, if believers in scientific method wish to express a single universally valid rule, Feyerabend jokingly suggests, it should be 'anything goes'.[118] Criticisms such as his led to the strong programme, a radical approach to the sociology of science.

The postmodernist critiques of science have themselves been the subject of intense controversy. This ongoing debate, known as the science wars, is the result of conflicting values and assumptions between the postmodernist and realist camps. Whereas postmodernists assert that scientific knowledge is simply another discourse (note that this term has special meaning in this context) and not representative of any form of fundamental truth, realists in the scientific community maintain that scientific knowledge does reveal real and fundamental truths about reality. Many books have been written by scientists which take on this problem and challenge the assertions of the postmodernists while defending science as a legitimate method of deriving truth.[119]

### Anthropology and sociology

In anthropology and sociology, following the field research in an academic scientific laboratory by Latour and Woolgar, Karin Knorr Cetina has conducted a comparative study of two scientific fields (namely high energy physics and molecular biology) to conclude that the epistemic practices and reasonings within both scientific communities are different enough to introduce the concept of "epistemic cultures", in contradiction with the idea that a so-called "scientific method" is unique and a unifying concept.[120]

### Role of chance in discovery

Somewhere between 33% and 50% of all scientific discoveries are estimated to have been *stumbled upon*, rather than sought out. This may explain why scientists so often express that they were lucky.[121] Louis Pasteur is credited with the famous saying that "Luck favours the prepared mind", but some psychologists have begun to study what it means to be 'prepared for luck' in the scientific context. Research is showing that scientists are taught various heuristics that tend to harness chance and the unexpected.[121][122] This is what Nassim Nicholas Taleb calls "Anti-fragility"; while some systems of investigation are fragile in the face of human error, human bias, and randomness, the scientific method is more than resistant or tough – it actually benefits from such randomness in many ways (it is anti-fragile). Taleb believes that the more anti-fragile the system, the more it will flourish in the real world.[27]

Psychologist Kevin Dunbar says the process of discovery often starts with researchers finding bugs in their experiments. These unexpected results lead researchers to try to fix what they *think* is an error in their method. Eventually, the researcher decides the error is too persistent and systematic to be a coincidence. The highly controlled, cautious and curious aspects of the scientific method are thus what make it well suited for identifying such persistent systematic errors. At this point, the researcher will begin to think of theoretical explanations for the error, often seeking the help of colleagues across different domains of expertise.[121][122]

## Relationship with mathematics

Science is the process of gathering, comparing, and evaluating proposed models against observables. A model can be a simulation, mathematical or chemical formula, or set of proposed steps. Science is like mathematics in that researchers in both disciplines try to distinguish what is *known* from what is *unknown* at each stage of discovery. Models, in both science and mathematics, need to be internally consistent and also ought to be *falsifiable* (capable of disproof). In mathematics, a statement need not yet be proven; at such a stage, that statement would be called a conjecture. But when a statement has attained mathematical proof, that statement gains a kind of immortality which is highly prized by mathematicians, and for which some mathematicians devote their lives.[123]

Mathematical work and scientific work can inspire each other.[124] For example, the technical concept of time arose in science, and timelessness was a hallmark of a mathematical topic. But today, the Poincaré conjecture has been proven using time as a mathematical concept in which objects can flow (see Ricci flow).

Nevertheless, the connection between mathematics and reality (and so science to the extent it describes reality) remains obscure. Eugene Wigner's paper, *The Unreasonable Effectiveness of Mathematics in the Natural Sciences*, is a very well known account of the issue from a Nobel Prize-winning physicist. In fact, some observers (including some well-known mathematicians such as Gregory Chaitin, and others such as Lakoff and Núñez) have suggested that mathematics is the result of practitioner bias and human limitation (including cultural ones), somewhat like the post-modernist view of science.

George Pólya's work on problem solving,[125] the construction of mathematical proofs, and heuristic[126][127] show that the mathematical method and the scientific method differ in detail, while nevertheless resembling each other in using iterative or recursive steps.

| | **Mathematical method** | **Scientific method** |
|---|---|---|
| **1** | Understanding | Characterization from experience and observation |
| **2** | Analysis | Hypothesis: a proposed explanation |
| **3** | Synthesis | Deduction: prediction from the hypothesis |
| **4** | Review/Extend | Test and experiment |

In Pólya's view, *understanding* involves restating unfamiliar definitions in your own words, resorting to geometrical figures, and questioning what we know and do not know already; *analysis*, which Pólya takes from Pappus,[128] involves free and heuristic construction of plausible arguments, working backward from the goal, and devising a plan for constructing the proof; *synthesis* is the strict Euclidean exposition of step-by-step details[129] of the proof; *review* involves reconsidering and re-examining the result and the path taken to it.

Gauss, when asked how he came about his theorems, once replied "durch planmässiges Tattonieren" (through systematic palpable experimentation).[130]

Imre Lakatos argued that mathematicians actually use contradiction, criticism and revision as principles for improving their work.[131] In like manner to science, where truth is sought, but certainty is not found, in *Proofs and refutations* (1976), what Lakatos tried to establish was that no theorem of informal mathematics is final or perfect. This means that we should not think that a theorem is ultimately true, only that no counterexample has yet been found. Once a counterexample, i.e. an entity contradicting/not explained by the theorem is found, we adjust the theorem, possibly extending the domain of its validity. This is a continuous way our knowledge accumulates, through the logic and process of proofs and refutations. (If axioms are given for a branch of mathematics, however, Lakatos claimed that proofs from those axioms were tautological, i.e. logically true, by rewriting them, as did Poincaré (*Proofs and Refutations*, 1976).)

Lakatos proposed an account of mathematical knowledge based on Polya's idea of heuristics. In *Proofs and Refutations*, Lakatos gave several basic rules for finding proofs and counterexamples to conjectures. He thought that mathematical 'thought experiments' are a valid way to discover mathematical conjectures and proofs.[132]

### Relationship with statistics

When the scientific method employs statistics as part of its arsenal, there are mathematical and practical issues that can have a deleterious effect on the reliability of the output of scientific methods. This is described in a popular 2005 scientific paper "Why Most Published Research Findings Are False" by John Ioannidis, which is considered foundational to the field of metascience.[133] Much research in metascience seeks to identify poor use of statistics and improve its use.

The particular points raised are statistical ("The smaller the studies conducted in a scientific field, the less likely the research findings are to be true" and "The greater the flexibility in designs, definitions, outcomes, and analytical modes in a scientific field, the less likely the research findings are to be true.") and economical ("The greater the financial and other interests and prejudices in a scientific field, the less likely the research findings are to be true" and "The hotter a scientific field (with more scientific teams involved), the less likely the research findings are to be true.") Hence: "Most research findings are false for most research designs and for most fields" and "As shown, the majority of modern biomedical research is operating in areas with very low pre- and poststudy probability for true findings." However: "Nevertheless, most new discoveries will continue to stem from hypothesis-generating research with low or very low pre-study odds," which means that *new* discoveries will come from research that, when that research started, had low or very low odds (a low or very low chance) of succeeding. Hence, if the scientific method is used to expand the frontiers of knowledge, research into areas that are outside the mainstream will yield most new discoveries.

## See also

- Armchair theorizing
- Contingency
- Empirical limits in science
- Evidence-based practices
- Fuzzy logic
- Information theory
- Logic
  - Historical method
  - Philosophical methodology
  - Scholarly method
- Methodology
- Metascience
- Operationalization
- Quantitative research
- Rhetoric of science
- Social research
- Strong inference
- Testability
- Verificationism

### Problems and issues

- Holism in science
- Junk science
- List of cognitive biases
- Normative science

- Philosophical skepticism
- Poverty of the stimulus
- Problem of induction
- Reference class problem
- Replication crisis
- Skeptical hypotheses
- Underdetermination

### History, philosophy, sociology

- Timeline of the history of scientific method
- Baconian method
- Epistemology
- Epistemic truth
- Mertonian norms
- Normal science
- Post-normal science
- Science studies
- Sociology of scientific knowledge

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8. Karl R. Popper, *Conjectures and Refutations: The Growth of Scientific Knowledge*, Routledge, 2003 ISBN 0-415-28594-1
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10. Gauch 2003, p. 3
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15. Peirce, C.S., *Collected Papers* v. 1, paragraph 74.
16. Albert Einstein, "On the Method of Theoretical Physics", in Essays in Science (Dover, 2009 [1934]), pp. 12–21.
17. Thurs, Daniel (2011). "12. Scientific Methods". In Shank, Michael; Numbers, Ronald; Harrison, Peter (eds.). *Wrestling with Nature: From Omens to Science*. Chicago: University of Chicago Press. pp. 307–36. ISBN 978-0-226-31783-0.
18. Achinstein, Peter (2004). *General Introduction*. *Science Rules: A Historical Introduction to Scientific Methods*. Johns Hopkins University Press. pp. 1–5. ISBN 978-0-8018-7943-2.
19. Smolin, Lee (May 2013). "There is No Scientific Method" (http://bigthink.com/in-their-own-words/there-is-no-scientific-method). Retrieved 2016-06-07.
20. Thurs, Daniel P. (2015), "That the scientific method accurately reflects what scientists actually do" (https://books.google.com/?id=pWouCwAAQBAJ&printsec=frontcover&dq=newton's+apple+and+other+myths+about+science#v=onepage&q=newton's%20apple%20and%20other%20myths%20about%20science&f=false), in Numbers, Ronald L.; Kampourakis, Kostas (eds.), *Newton's Apple and Other Myths about Science*, Harvard University Press, pp. 210–18, ISBN 978-0-674-91547-3, "It's probably best to get the bad news out of the way first, the so-called scientific method is a myth.&nbps;... If typical formulations were accurate, the only location true science would be taking place in would be grade-school classrooms."
21. Nola, Robert; Sankey, Howard (2007). *Theories of Scientific Method: An Introduction*. Philosophy and science. **2**. Montréal: McGill–Queen's University Press. pp. 1 (https://books.google.com/books?id=aKjgBQAAQBAJ&pg=PA1), 300 (https://books.google.com/books?id=aKjgBQAAQBAJ&pg=PA300). doi:10.4324/9781315711959 (https://doi.org/10.4324%2F9781315711959). ISBN 9780773533448. OCLC 144602109 (https://www.worldcat.org/oclc/144602109). "There is a large core of people who think there is such a thing as a scientific method that can be justified, although not all agree as to what this might be. But there are also a growing number of people who think that there is no method to be justified. For some, the whole idea is yesteryear's debate, the continuation of which can be summed up as yet more of the proverbial 'flogging a dead horse'. We beg to differ. ... We shall claim that Feyerabend did endorse various scientific values, did accept rules of method (on a certain understanding of what these are) and did attempt to justify them using a metamethodology somewhat akin to the principle of reflective equilibrium."
22. Gauch 2003, p. xv: "The thesis of this book, as set forth in Chapter One, is that there are general principles applicable to all the sciences."
23. Peirce, Charles Sanders (1877). "The Fixation of Belief"  (https://en.wikisource.org/wiki/The_Fixation_of_Belief). *Popular Science Monthly*. **12**: 1–15 – via Wikisource..
24. Gauch 2003, p. 1: The scientific method can function in the same way; This is the principle of noncontradiction.
25. Francis Bacon(1629) *New Organon*, lists 4 types of error: Idols of the tribe (error due to the entire human race), the cave (errors due to an individual's own intellect), the marketplace (errors due to false words), and the theater (errors due to incredulous acceptance).

26. Peirce, C.S., *Collected Papers* v. 5, in paragraph 582, from 1898:

> ... [rational] inquiry of every type, fully carried out, has the vital power of self-correction and of growth. This is a property so deeply saturating its inmost nature that it may truly be said that there is but one thing needful for learning the truth, and that is a hearty and active desire to learn what is true.

27. Taleb contributes a brief description of anti-fragility (http://www.edge.org/q2011/q11_3.html)
28. For example, the concept of falsification (first proposed in 1934) formalizes the attempt to *disprove* hypotheses rather than prove them. *Karl R. Popper (1963), 'The Logic of Scientific Discovery'. The Logic of Scientific Discovery (http://www.cosmopolitanuniversity.ac/library/LogicofScientificDiscoveryPopper1959.pdf) pp. 17–20, 249–52, 437–38, and elsewhere.*
    - Leon Lederman, for teaching physics first, illustrates how to avoid confirmation bias: Ian Shelton, in Chile, was initially skeptical that supernova 1987a was real, but possibly an artifact of instrumentation (null hypothesis), so he went outside and disproved his null hypothesis by observing SN 1987a with the naked eye. The Kamiokande experiment, in Japan, independently observed neutrinos from SN 1987a at the same time.
29. Lindberg 2007, pp. 2–3: "There is a danger that must be avoided. ... If we wish to do justice to the historical enterprise, we must take the past for what it was. And that means we must resist the temptation to scour the past for examples or precursors of modern science. ...My concern will be with the beginnings of scientific *theories*, the methods by which they were formulated, and the uses to which they were put; ... "
30. Elizabeth Asmis (1985) *Epicurus' Scientific Method*. Cornell University Press

31. Alhazen argued the importance of forming questions and subsequently testing them: "How does light travel through transparent bodies? Light travels through transparent bodies in straight lines only.... We have explained this exhaustively in our *Book of Optics*. But let us now mention something to prove this convincingly: the fact that light travels in straight lines is clearly observed in the lights which enter into dark rooms through holes.... [T]he entering light will be clearly observable in the dust which fills the air. – Alhazen, *Treatise on Light* (رسالة في الضوء), translated into English from German by M. Schwarz, from "Abhandlung über das Licht" (http://menadoc.bibliothek.uni-halle.de/dmg/periodical/pageview/30949), J. Baarmann (editor and translator from Arabic to German, 1882) *Zeitschrift der Deutschen Morgenländischen Gesellschaft* Vol **36** as quoted in Sambursky 1974, p. 136.

   - He demonstrated his conjecture that "light travels through transparent bodies in straight lines only" by placing a straight stick or a taut thread next to the light beam, as quoted in Sambursky 1974, p. 136 to prove that light travels in a straight line.
   - David Hockney, (2001, 2006) in *Secret Knowledge: rediscovering the lost techniques of the old masters* ISBN 0-14-200512-6 (expanded edition) cites Alhazen several times as the likely source for the portraiture technique using the camera obscura, which Hockney rediscovered with the aid of an optical suggestion from Charles M. Falco. *Kitab al-Manazir*, which is Alhazen's *Book of Optics*, at that time denoted *Opticae Thesaurus, Alhazen Arabis*, was translated from Arabic into Latin for European use as early as 1270. Hockney cites Friedrich Risner's 1572 Basle edition of *Opticae Thesaurus*. Hockney quotes Alhazen as the first clear description of the camera obscura in Hockney, p. 240.

   "Truth is sought for its own sake. And those who are engaged upon the quest for anything for its own sake are not interested in other things. Finding the truth is difficult, and the road to it is rough." – Alhazen (Ibn Al-Haytham 965 – c. 1040) *Critique of Ptolemy*, translated by S. Pines, *Actes X Congrès internationale d'histoire des sciences*, Vol **I** Ithaca 1962, as quoted in Sambursky 1974, p. 139. (This quotation is from Alhazen's critique of Ptolemy's books *Almagest*, *Planetary Hypotheses*, and *Optics* as translated into English by A. Mark Smith (https://books.google.com/?id=mhLVHR5QAQkC&pg=PA59&dq=Opticae+thesaurus+alhazen).)

32. "The optics of Giovan Battista della Porta (1535–1615): a reassessment. Workshop at Technical University of Berlin, 24–25 October 2014" (http://www.wissensgeschichte-berlin.de/sites/default/files/2014_10_24_DellaPortaWS_Program_Abstracts.pdf) (PDF).
33. Kepler, Johannes (1604) *Ad Vitellionem paralipomena, quibus astronomiae pars opticae traditur* (Supplements to Witelo, in which the optical part of astronomy is treated) as cited in Smith, A. Mark (1 January 2004). "What Is the History of Medieval Optics Really about?". *Proceedings of the American Philosophical Society*. **148** (2): 180–94. JSTOR 1558283 (https://www.jstor.org/stable/1558283). PMID 15338543 (https://pubmed.ncbi.nlm.nih.gov/15338543).

   - The full title translation is from p. 60 of James R. Voelkel (2001) *Johannes Kepler and the New Astronomy* Oxford University Press. Kepler was driven to this experiment after observing the partial solar eclipse at Graz, July 10, 1600. He used Tycho Brahe's method of observation, which was to project the image of the Sun on a piece of paper through a pinhole aperture, instead of looking directly at the Sun. He disagreed with Brahe's conclusion that total eclipses of the Sun were impossible, because there were historical accounts of total eclipses. Instead he deduced that the size of the aperture controls the sharpness of the projected image (the larger the aperture, the more accurate the image – this fact is now fundamental for optical system design). Voelkel, p. 61, notes that Kepler's experiments produced the first correct account of vision and the eye, because he realized he could not accurately write about astronomical observation by ignoring the eye.

34. ...an approach which was advocated by Galileo in 1638 with the publication of *Two New Sciences*.Galilei, Galileo (1638), *Discorsi e Dimonstrazioni Matematiche, intorno a due nuoue scienze*, Leida: Apresso gli Elsevirri, ISBN 978-0-486-60099-4, Dover reprint of the 1914 Macmillan translation by Henry Crew and Alfonso de Salvio of *Two New Sciences*, Galileo Galilei Linceo (1638). Additional publication information is from the collection of first editions of the Library of Congress surveyed by Bruno 1989, pp. 261–64.
35. Sanches, Limbrick & Thomson 1988
36. Godfrey-Smith 2003 p. 236.
37. Staddon, J. (2017) *Scientific Method: How science works, fails to work or pretends to work.* Taylor and Francis.
38. Schuster and Powers (2005), Translational and Experimental Clinical Research, Ch. 1. Link. (https://books.google.com/?id=C7pZftbI0ZMC&printsec=frontcover&dq=Translational+and+Experimental+Clinical+Research) This chapter also discusses the different types of research questions and how they are produced.
39. This phrasing is attributed to Marshall Nirenberg.
40. Note: for a discussion of multiple hypotheses, see Bayesian inference#Informal
41. McCarty 1985
42. October 1951, as noted in McElheny 2004, p. 40:"That's what a helix should look like!" Crick exclaimed in delight (This is the Cochran-Crick-Vand-Stokes theory of the transform of a helix).
43. June 1952, as noted in McElheny 2004, p. 43: Watson had succeeded in getting X-ray pictures of TMV showing a diffraction pattern consistent with the transform of a helix.
44. Watson did enough work on Tobacco mosaic virus to produce the diffraction pattern for a helix, per Crick's work on the transform of a helix. pp. 137–38, Horace Freeland Judson (1979) *The Eighth Day of Creation* ISBN 0-671-22540-5
45. – Cochran W, Crick FHC and Vand V. (1952) "The Structure of Synthetic Polypeptides. I. The Transform of Atoms on a Helix", *Acta Crystallogr.*, **5**, 581–86.
46. Friday, January 30, 1953. Tea time, as noted in McElheny 2004, p. 52: Franklin confronts Watson and his paper – "Of course it [Pauling's pre-print] is wrong. DNA is not a helix." However, Watson then visits Wilkins' office, sees photo 51, and immediately recognizes the diffraction pattern of a helical structure. But additional questions remained, requiring additional iterations of their research. For example, the number of strands in the backbone of the helix (Crick suspected 2 strands, but cautioned Watson to examine that more critically), the location of the base pairs (inside the backbone or outside the backbone), etc. One key point was that they realized that the quickest way to reach a result was not to continue a mathematical analysis, but to build a physical model.
47. "The instant I saw the picture my mouth fell open and my pulse began to race." – Watson 1968, p. 167 Page 168 shows the X-shaped pattern of the B-form of DNA, clearly indicating crucial details of its helical structure to Watson and Crick.
    - McElheny 2004 p. 52 dates the Franklin-Watson confrontation as Friday, January 30, 1953. Later that evening, Watson urges Wilkins to begin model-building immediately. But Wilkins agrees to do so only after Franklin's departure.
48. Saturday, February 28, 1953, as noted in McElheny 2004, pp. 57–59: Watson found the base pairing mechanism which explained Chargaff's rules using his cardboard models.
49. Galileo Galilei (1638) *Two new sciences*
50. "Reconstruction of Galileo Galilei's experiment – the inclined plane" (http://www.fyysika.ee/vorgustik/wp-content/uploads/2011/11/Reconstruction-of-Galileo-Galilei.pdf) (PDF).

51. Ioannidis, John P. A. (August 2005). "Why most published research findings are false" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1182327). *PLOS Medicine*. **2** (8): e124. doi:10.1371/journal.pmed.0020124 (https://doi.org/10.1371%2Fjournal.pmed.0020124). PMC 1182327 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1182327). PMID 16060722 (https://pubmed.ncbi.nlm.nih.gov/16060722).
52. In *Two new sciences*, there are three 'reviewers': Simplicio, Sagredo, and Salviati, who serve as foil, antagonist, and protagonist. Galileo speaks for himself only briefly. But note that Einstein's 1905 papers were not peer reviewed before their publication.
53. Fleck 1979, pp. xxvii–xxviii
54. "NIH Data Sharing Policy (http://grants.nih.gov/grants/policy/data_sharing/index.htm)."
55. Stanovich, Keith E. (2007). *How to Think Straight About Psychology*. Boston: Pearson Education. p. 123
56. Tow, David Hunter (2010-09-11). *The Future of Life: A Unified Theory of Evolution* (https://books.google.com/books?id=c0wecGHSpTQC). Future of Life Series. Future of Life Media (published 2010). p. 262. Retrieved 2016-12-11. "On further examination however, the scientific method bears a striking similarity to the larger process of evolution itself. [...] Of great significance is the evolutionary algorithm, which uses a simplified subset of the process of natural evolution applied to find the solution to problems that are too complex to solve by traditional analytic methods. In essence it is a process of accelerated and rigorous trial and error building on previous knowledge to refine an existing hypothesis, or discarding it altogether to find a better model. [...] The evolutionary algorithm is a technique derived from the evolution of knowledge processing applied within the context of science and technology, itself an outcome of evolution. The scientific method continues to evolve through adaptive reward, trial and error and application of the method to itself."
57. Brody 1993, pp. 44–45
58. Goldhaber & Nieto 2010, p. 942
59. Hall, B.K.; Hallgrímsson, B., eds. (2008). *Strickberger's Evolution* (https://archive.org/details/strickbergersevo0000hall/page/762) (4th ed.). Jones & Bartlett. p. 762 (https://archive.org/details/strickbergersevo0000hall/page/762). ISBN 978-0-7637-0066-9.
60. Cracraft, J.; Donoghue, M.J., eds. (2005). *Assembling the tree of life* (https://books.google.com/books?id=6lXTP0YU6_kC&printsec=frontcover&dq=Assembling+the+tree+of+life#v=onepage&q&f=false). Oxford University Press. p. 592. ISBN 978-0-19-517234-8.
61. Needham & Wang 1954 p. 166 shows how the 'flying gallop' image propagated from China to the West.
62. Goldhaber & Nieto 2010, p. 940
63. "A myth is a belief given uncritical acceptance by members of a group ..." – Weiss, *Business Ethics* p. 15, as cited by Ronald R. Sims (2003) *Ethics and corporate social responsibility: why giants fall* p. 21
64. Imre Lakatos (1976), *Proofs and Refutations*. Taleb 2007, p. 72 lists ways to avoid the narrative fallacy and confirmation bias.
65. The scientific method requires testing and validation *a posteriori* before ideas are accepted. "Invariably one came up against fundamental physical limits to the accuracy of measurement. ... The art of physical measurement seemed to be a matter of compromise, of choosing between reciprocally related uncertainties. ... Multiplying together the conjugate pairs of uncertainty limits mentioned, however, I found that they formed invariant products of not one but two distinct kinds. ... The first group of limits were calculable *a priori* from a specification of the instrument. The second group could be calculated only *a posteriori* from a specification of what was *done* with the instrument. ... In the first case each unit [of information] would add one additional *dimension* (conceptual category), whereas in the second each unit would add one additional *atomic fact*.", pp. 1–4: MacKay, Donald M. (1969), *Information, Mechanism, and Meaning*, Cambridge, MA: MIT Press, ISBN 0-262-63032-X

66. Godfrey-Smith, Peter (2009). *Theory and Reality: An Introduction to the Philosophy of Science* (https://books.google.com/?id=k23egtSWrb8C). Chicago: University of Chicago Press. ISBN 978-0-226-30062-7.
67. Brody, Thomas A. (1993). *The Philosophy Behind Physics* (https://books.google.com/?id=zmHrCAAAQBAJ). Berlin; New York: Springer-Verlag. ISBN 978-3-540-55914-6.
68. Kuhn, Thomas S. (2012). *The Structure of Scientific Revolutions* (https://books.google.com/books/about/The_Structure_of_Scientific_Revolutions.html?id=3eP5Y_OOuzwC) (50th Anniversary ed.). Chicago: University of Chicago Press. ISBN 978-0-226-45811-3. Retrieved 29 January 2018.
69. Galison, Peter (1987). *How Experiments End* (https://books.google.com/books/about/How_Experiments_End.html?id=DN-9m2jSo8YC). Chicago: University of Chicago Press. ISBN 978-0-226-27915-2. Retrieved 29 January 2018.
70. In the inquiry-based education paradigm, the stage of "characterization, observation, definition, ..." is more briefly summed up under the rubric of a Question
71. "To raise new questions, new possibilities, to regard old problems from a new angle, requires creative imagination and marks real advance in science." – Einstein & Infeld 1938, p. 92.
72. Crawford S, Stucki L (1990), "Peer review and the changing research record", "J Am Soc Info Science", vol. 41, pp. 223–28
73. *See, e.g.*, Gauch 2003, esp. chapters 5–8
74. Andreas Vesalius, *Epistola, Rationem, Modumque Propinandi Radicis Chynae Decocti* (1546), 141. Quoted and translated in C.D. O'Malley, *Andreas Vesalius of Brussels*, (1964), 116. As quoted by Bynum & Porter 2005, p. 597: Andreas Vesalius, 597#1.
75. Crick, Francis (1994), *The Astonishing Hypothesis* ISBN 0-684-19431-7 p. 20
76. McElheny 2004 p. 34
77. eso2006 — Science Release (16 April 2020) ESO Telescope Sees Star Dance Around Supermassive Black Hole, Proves Einstein Right (https://www.eso.org/public/news/eso2006/)
78. Einstein, Albert (1949). *The World as I See It*. New York: Philosophical Library. pp. 24–28.
79. Glen 1994, pp. 37–38.
80. John R. Platt (16 October 1964) Strong Inference (http://science.sciencemag.org/content/146/3642/347) *Science* vol **146** (3642) p. 347 doi:10.1126/science.146.3642.347 (https://doi.org/10.1126%2Fscience.146.3642.347)
81. "The structure that we propose is a three-chain structure, each chain being a helix" – Linus Pauling, as quoted on p. 157 by Horace Freeland Judson (1979), *The Eighth Day of Creation* ISBN 0-671-22540-5
82. McElheny 2004, pp. 49–50: January 28, 1953 – Watson read Pauling's pre-print, and realized that in Pauling's model, DNA's phosphate groups had to be un-ionized. But DNA is an acid, which contradicts Pauling's model.
83. June 1952. as noted in McElheny 2004, p. 43: Watson had succeeded in getting X-ray pictures of TMV showing a diffraction pattern consistent with the transform of a helix.
84. McElheny 2004 p. 68: *Nature* April 25, 1953.
85. In March 1917, the Royal Astronomical Society announced that on May 29, 1919, the occasion of a total eclipse of the sun would afford favorable conditions for testing Einstein's General theory of relativity. One expedition, to Sobral, Ceará, Brazil, and Eddington's expedition to the island of Principe yielded a set of photographs, which, when compared to photographs taken at Sobral and at Greenwich Observatory showed that the deviation of light was measured to be 1.69 arc-seconds, as compared to Einstein's desk prediction of 1.75 arc-seconds. – Antonina Vallentin (1954), *Einstein*, as quoted by Samuel Rapport and Helen Wright (1965), *Physics*, New York: Washington Square Press, pp. 294–95.
86. Mill, John Stuart, "A System of Logic", University Press of the Pacific, Honolulu, 2002, ISBN 1-4102-0252-6.

87. al-Battani, *De Motu Stellarum* translation from Arabic to Latin in 1116, as cited by "Battani, al-" (c. 858–929) *Encyclopædia Britannica*, 15th. ed. Al-Battani is known for his accurate observations at al-Raqqah in Syria, beginning in 877. His work includes measurement of the annual precession of the equinoxes.
88. PBS WBGH, NOVA: the Secret of Photo 51 (https://www.pbs.org/wgbh/nova/photo51/) X-shape
89. McElheny 2004 p. 53: The weekend (January 31 – February 1) after seeing photo 51, Watson informed Bragg of the X-ray diffraction image of DNA in B form. Bragg gave them permission to restart their research on DNA (that is, model building).
90. McElheny 2004 p. 54: On Sunday, February 8, 1953, Maurice Wilkes gave Watson and Crick permission to work on models, as Wilkes would not be building models until Franklin left DNA research.
91. McElheny 2004 p. 56: Jerry Donohue, on sabbatical from Pauling's lab and visiting Cambridge, advises Watson that textbook form of the base pairs was incorrect for DNA base pairs; rather, the keto form of the base pairs should be used instead. This form allowed the bases' hydrogen bonds to pair 'unlike' with 'unlike', rather than to pair 'like' with 'like', as Watson was inclined to model, on the basis of the textbook statements. On February 27, 1953, Watson was convinced enough to make cardboard models of the nucleotides in their keto form.
92. "Suddenly I became aware that an adenine-thymine pair held together by two hydrogen bonds was identical in shape to a guanine-cytosine pair held together by at least two hydrogen bonds. ..." – Watson 1968, pp. 194–97.
    - McElheny 2004 p. 57 Saturday, February 28, 1953, Watson tried 'like with like' and admitted these base pairs didn't have hydrogen bonds that line up. But after trying 'unlike with unlike', and getting Jerry Donohue's approval, the base pairs turned out to be identical in shape (as Watson stated above in his 1968 *Double Helix* memoir quoted above). Watson now felt confident enough to inform Crick. (Of course, 'unlike with unlike' increases the number of possible codons, if this scheme were a genetic code.)
93. See, e.g., *Physics Today*, **59**(1), p. 42. Richmann electrocuted in St. Petersburg (1753) (http://ptonline.aip.org/journals/doc/PHTOAD-ft/vol_59/iss_1/42_1.shtml?bypassSSO=1)
94. Aristotle, "Prior Analytics", Hugh Tredennick (trans.), pp. 181–531 in *Aristotle, Volume 1*, Loeb Classical Library, William Heinemann, London, 1938.
95. "What one does not in the least doubt one should not pretend to doubt; but a man should train himself to doubt," said Peirce in a brief intellectual autobiography; see Ketner, Kenneth Laine (2009) "Charles Sanders Peirce: Interdisciplinary Scientist" in *The Logic of Interdisciplinarity*). Peirce held that actual, genuine doubt originates externally, usually in surprise, but also that it is to be sought and cultivated, "provided only that it be the weighty and noble metal itself, and no counterfeit nor paper substitute"; in "Issues of Pragmaticism", *The Monist*, v. XV, n. 4, pp. 481–99, see p. 484 (https://archive.org/stream/monistquart15hegeuoft#page/484/mode/1up), and p. 491 (https://archive.org/stream/monistquart15hegeuoft#page/491/mode/1up). (Reprinted in *Collected Papers* v. 5, paragraphs 438–63, see 443 and 451).
96. But see Scientific method and religion.
97. Peirce (1898), "Philosophy and the Conduct of Life", Lecture 1 of the Cambridge (MA) Conferences Lectures, published in *Collected Papers* v. 1, paragraphs 616–48 in part and in *Reasoning and the Logic of Things*, Ketner (ed., intro.) and Putnam (intro., comm.), pp. 105–22, reprinted in *Essential Peirce* v. 2, pp. 27–41.
98. " ... in order to learn, one must desire to learn ..." – Peirce (1899), "F.R.L." [First Rule of Logic], *Collected Papers* v. 1, paragraphs 135–40, "Eprint" (https://web.archive.org/web/20120106071421/http://www.princeton.edu/~batke/peirce/frl_99.htm). Archived from the original (http://www.princeton.edu/~batke/peirce/frl_99.htm) on January 6, 2012. Retrieved 2012-01-06.

99. Peirce, Charles Sanders (1877). "How to Make Our Ideas Clear" (https://en.wikisource.org/wiki/How_to_Make_Our_Ideas_Clear). *Popular Science Monthly*. **12**: 286–302 wslink==How to Make Our Ideas Clear – via Wikisource.
00. Peirce (1868), "Some Consequences of Four Incapacities", *Journal of Speculative Philosophy* v. 2, n. 3, pp. 140–57. Reprinted *Collected Papers* v. 5, paragraphs 264–317, *The Essential Peirce* v. 1, pp. 28–55, and elsewhere. *Arisbe* Eprint (http://www.cspeirce.com/menu/library/bycsp/conseq/cn-frame.htm)
01. Peirce (1878), "The Doctrine of Chances", *Popular Science Monthly* v. 12, pp. 604–15, see pp. 610–11 (https://archive.org/stream/popscimonthly12yoummiss#page/618/mode/1up) via *Internet Archive*. Reprinted *Collected Papers* v. 2, paragraphs 645–68, *Essential Peirce* v. 1, pp. 142–54. "...death makes the number of our risks, the number of our inferences, finite, and so makes their mean result uncertain. The very idea of probability and of reasoning rests on the assumption that this number is indefinitely great. .... ...logicality inexorably requires that our interests shall not be limited. .... Logic is rooted in the social principle."
02. Peirce (c. 1906), "PAP (Prolegomena for an Apology to Pragmatism)" (Manuscript 293, not the like-named article), *The New Elements of Mathematics* (NEM) 4:319–20, see first quote under "Abduction (http://www.helsinki.fi/science/commens/terms/abduction.html)" at *Commens Dictionary of Peirce's Terms*.
03. Peirce, Carnegie application (L75, 1902), *New Elements of Mathematics* v. 4, pp. 37–38:

> For it is not sufficient that a hypothesis should be a justifiable one. Any hypothesis which explains the facts is justified critically. But among justifiable hypotheses we have to select that one which is suitable for being tested by experiment.

04. Peirce (1902), Carnegie application, see MS L75.329330, from Draft D (http://www.cspeirce.com/menu/library/bycsp/l75/ver1/l75v1-08.htm#m27) of Memoir 27:

> Consequently, to discover is simply to expedite an event that would occur sooner or later, if we had not troubled ourselves to make the discovery. Consequently, the art of discovery is purely a question of economics. The economics of research is, so far as logic is concerned, the leading doctrine with reference to the art of discovery. Consequently, the conduct of abduction, which is chiefly a question of heuretic and is the first question of heuretic, is to be governed by economical considerations.

05. Peirce (1903), "Pragmatism – The Logic of Abduction", *Collected Papers* v. 5, paragraphs 195–205, especially 196. Eprint (http://www.textlog.de/7663.html).
06. Peirce, "On the Logic of Drawing Ancient History from Documents", *Essential Peirce* v. 2, see pp. 107–09. On Twenty Questions, p. 109:

> Thus, twenty skillful hypotheses will ascertain what 200,000 stupid ones might fail to do.

07. Peirce (1878), "The Probability of Induction", *Popular Science Monthly*, v. 12, pp. 705–18, see 718 (https://books.google.com/?id=ZKMVAAAAYAAJ&pg=PA718) *Google Books*; 718 (https://archive.org/stream/popscimonthly12yoummiss#page/728/mode/1up) via *Internet Archive*. Reprinted often, including (*Collected Papers* v. 2, paragraphs 669–93), (*The Essential Peirce* v. 1, pp. 155–69).

08. Peirce (1905 draft "G" of "A Neglected Argument"), "Crude, Quantitative, and Qualitative Induction", *Collected Papers* v. 2, paragraphs 755–60, see 759. Find under "Induction (http://www.helsinki.fi/science/commens/terms/induction.html)" at *Commens Dictionary of Peirce's Terms*.
09. "James (2003) "Complex Systems Theory?" " (http://csc.ucdavis.edu/~chaos/chaos/talks/CSTheorySFIRetreat.pdf) (PDF).
10. Review of *The Quark and the Jaguar*, by Murray Gell-Mann (1994) (https://physicstoday.scitation.org/doi/10.1063/1.2808634)
    - Murray Gell-Mann, "What the *Quark and Jaguar* is about" – Youtube clip (https://www.youtube.com/watch?v=AGSXGMpA0pY)
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23. "When we are working intensively, we feel keenly the progress of our work; we are elated when our progress is rapid, we are depressed when it is slow." – the mathematician Pólya 1957, p. 131 in the section on 'Modern heuristic'.

24. "Philosophy [i.e., physics] is written in this grand book – I mean the universe – which stands continually open to our gaze, but it cannot be understood unless one first learns to comprehend the language and interpret the characters in which it is written. It is written in the language of mathematics, and its characters are triangles, circles, and other geometrical figures, without which it is humanly impossible to understand a single word of it; without these, one is wandering around in a dark labyrinth." – Galileo Galilei, *Il Saggiatore* (*The Assayer*, 1623), as translated by Stillman Drake (1957), *Discoveries and Opinions of Galileo* pp. 237–38, as quoted by di Francia 1981, p. 10.
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