The scientific method

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A **method** or procedure that has characterised natural science since the 17th century, consisting in **systematic observation, measurement, and experiment, and the formulation, testing, and modification of hypotheses** [1]

The **scientific** method is the process by which **science** is carried out.

[1] http://www.oxforddictionaries.com/definition/english/scientific-method.

Scientific - adjective

- **... of or relating to science or the sciences**:
  $->$ *scientific studies*.
- **... occupied or concerned with science**:
  $->$ *scientific experts*.
- **... regulated by or conforming to the principles of exact science**:
  $->$ *scientific procedures*.
- systematic or accurate in the manner of an exact science[2].

[2] http://dictionary.reference.com/browse/scientific

The history of **scientific method** is a history of the methodology of **scientific inquiry**

History of science $! =$ history of the scientific method

The scientific method - acute debate

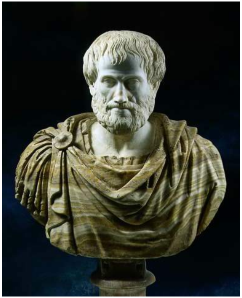
The scientific method has always been the subject of an **acute debate** throughout the **history of science**.

Many scientists and natural philosophers have argued for the superiority/preeminence of one or another approach for establishing scientific knowledge.

*Despite this **disagreement**, there have been many **recurrent pattern/trends** in the long **development of the scientific method** into nowadays forms*.

No one can be credited as the inventor of the scientific method (originally called the **experimental method**). This method was not ‘invented’ by someone but developed as the **natural method** for obtaining **reliable knowledge**.

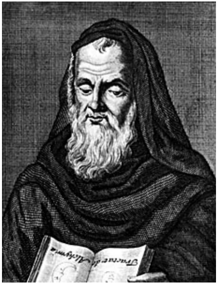
Many authors trace the beginning of the scientific method and experimenting back to ancient artisans, Greeks, Arabs, Spaniards, and others.



- **name**: Aristotele
- **born:** 383 BCE, Stagira, Greece
- **died:** 322 BCE, Calcide, Greece
- **fields:** philosophy, logic

One of the most **original thinkers**, first for devising methods for trying to arrive at **reliable knowledge** based on observation.

The scientific method - history - 2 of 5



- **name**: Roger Bacon
- **born:** 1214, Ilchester, United Kingdom
- **died:** 1292, Oxford, United Kingdom
- **fields:** philosophy, religion

Drawing on the writings of Muslim scientists, he described a **repeating cycle of observation, hypothesis, experimentation, and verification**. He gave considerable emphasis on the study of nature through **empirical methods**.

- **name**: Galileo Galilei
- **born:** Feb. 15th, 1564, Pisa, Italy
- **died:** Jan. 8th, 1642, Arcetri, Italy
- **fields:** physic, mathematics, astronomy, philosophy, engineering

In our modern culture, he is credited as the **father of the scientific method**. *'Even while Bacon was philosophising, the true method was being practiced by Galileo. With a combination of observation, hypothesis, mathematical deduction and confirmatory experiment founded the science of dynamics'.* [3]

[3] The Encyclopedia Britannica (1970)

- **name**: Francis Bacon
- **born:** January 22nd, 1561, London, England
- **died:** April 9th, 1626, Highgate, United Kingdom
- **fields:** philosophy, jurisprudence, oratorism

He is famous for explaining his method in ‘Novum Organum’, published in 1622. His works established and popularised **inductive methodologies for scientific inquiry**, often called the Baconian method, basically the scientific method.

- **name**: René Descartes
- **born:** March 31st, 1596, La Haye en Touraine, Kingdom of France
- **died:** February 11th, 1650, Stockholm, Sweden
- **fields:** philosophy, mathematics

His major contribution was the Discourse (1637)[4]. The idea is that **all science become demonstrative**, namely as a series of **valid deductions** from self-evident truths, rather than as something rooted in observation and experiment.

[4] Discourse on the Method for Rightly Directing One's Reason and Searching for Truth in the Science

1. **Observation/description** of a phenomenon or group of phenomena.
2. **Formulation of an hypothesis** to explain the phenomena.
3. **Experimental tests** for testing hypothesis by several independent experimenters and properly performed experiments.
4. **refutation of acceptance of hypothesis**

The classical scientific method - Testing hypotheses

If the experiments:

- support the hypothesis
  $->$ it may be regarded as theory/law of nature
- do not support the hypothesis
  $->$ it must be rejected or modified.

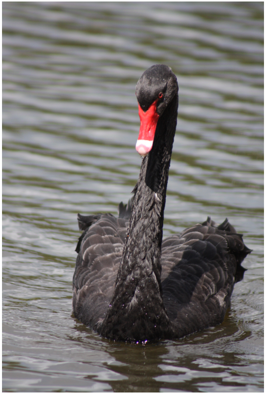
Core notion: the predictive power of the hypothesis or theory, as tested by experiment.



1. **Observation/description**: hundred of swans have been observed and all of them were white
2. **Formulation of the hypothesis**: by induction the statement *‘all swans are white’* is true.
3. **Experimental tests**: proof by induction ‘if all the swans are observed to be white, then all swans are white’
4. **refutation or acceptance of hypothesis**: acceptance

Can we actually make a universal claim based on a finite number of observations?

In science it is belief that theories can never be proved, but only disproved. There is always a possibility that a new observation or experiment will conflict with a long-standing theory.



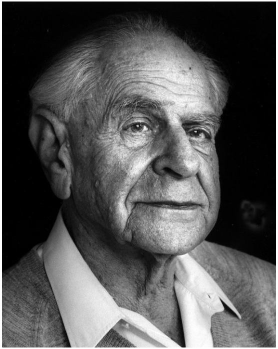
- No matter how elegant a theory is
- No matter how well-formulated a hypothesis is
- No matter how much strong is the belief on the hypothesis

If the hypothesis and predictions do not agree with experimental empirical results, it is not a valid description of the nature [5].

[5] The necessity of experiment also implies that a theory is testable. Not testable theories - they have no observable ramifications - do not qualify as scientific theories.

- to mistake the hypothesis for an explanation of a phenomenon, without performing experimental tests
- sometimes ‘common sense’ and ‘logic’ tempt us into believing that no test is needed
- to ignore or rule out data which do not support the hypothesis
- lack of systematic quantitatively estimations of errors

Empirical falsification



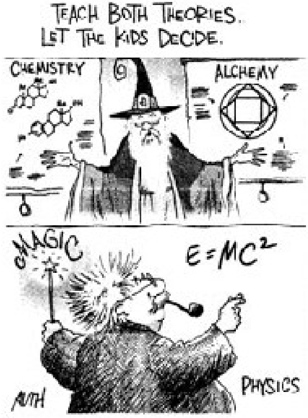
- **name**: Karl Raimund Popper
- **born:** July 28th, 1902, Vienna, Austria-Hungary
- **died:** September 17th, 1994, London, United Kingdom
- **fields:** philosophy, science

He is known for his rejection of the classical inductivist views on the scientific method, in favour of **empirical falsification - falsifiability** - the most commonly invoked ‘criterion of demarcation’ of science from non-science (pseudo-science)

Falsifiability is the logical possibility that an assertion can be shown false by an observation or a physical experiment. That something is ‘falsifiable’ does not mean it is false; rather, that if it is false, then this can be shown by observation or experiment.

A theory in the empirical sciences can never be proven, but it can be falsified, meaning that it can and should be scrutinized by decisive experiments.

Theories whose predictions **conflict with experimental observation** are soon discarded, and science progresses as a **process of elimination**.



Pseudoscience is a claim, belief or practice which is **incorrectly presented as scientific**, it does not adhere to a valid scientific method, it cannot be reliably tested, or otherwise **lacks scientific status**.[6]

[6] Oxford English Dictionary

Pseudo-science is usually distinguished by:

- the use of vague, contradictory/unprovable claims
- an over-reliance on confirmation rather than rigorous attempts at refutation
- a lack of openness to evaluation by other experts
- a general absence of systematic processes to rationally develop theories

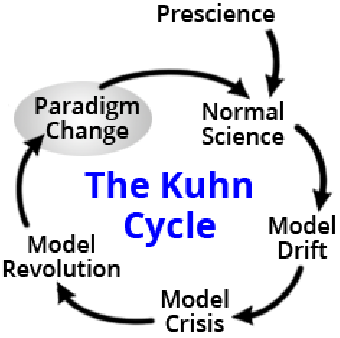
The structure of scientific revolutions

- **name**: Thomas Samuel Kuhn
- **born:** July 18th, 1922, Cincinnati, Ohio
- **died:** June 17th, 1996, Cambridge, Massachusetts
- **fields:** philosophy, physics, history, science

He made several notable claims concerning the **progress of scientific knowledge** and the ‘Structure of Scientific Revolutions’. Scientific fields are subject of periodic **‘paradigm shifts’** rather than solely progressing in a continuous, linear way.

Kuhn's opinion of **science** was that, in fact, it is not a cumulative process, but in reality, **a cyclical process**.

A particular research perspective (paradigm) dominates for a period of time, until a new one is developed which supersedes it.



Examples of paradigm shifts

- The transition from a **Ptolemaic cosmology** to a **Copernican** one
- The transition between the worldview of **Newtonian physics** and the **Einsteinian Relativistic** worldview
- The development of **Quantum mechanics**, which redefined **Classical mechanics**
- The acceptance of Charles Darwin's **theory of natural selection** as a replacement of **Lamarckism's** mechanism for evolution

- **name**: Imre Lakatos
- **born:** November 9th, 1922, Debrecen, Hungary
- **died:** February 2nd, 1974, London, England
- **fields:** philosophy, mathematics, science

Known for introducing the concept of the ‘research programme’ in his methodology of **scientific research programmes**. He presented his image as a modification and improvement of Popper’s basic falsificationist view.

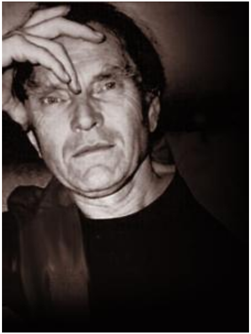
Imre Lakatos's attempt at harmonious relations

- *" Popper is wrong to believe that theories must be rejected when they fail tests - there may be a hard core to the theory that is correct thus they should not be abandoned "*
- *" Kuhn is wrong to think there is no rational comparison: research programmes can be compared over time to see how well they develop, how many novel predictions they make "*.

Lakatos' model aims to combine Popper's adherence to **empirical validity** with Kuhn's appreciation for **conventional consistency**.

A **research programme** is based on a hard core of theoretical assumptions that cannot be abandoned or altered without abandoning the programme altogether.

A research programme is essentially a **sequence of theories** within a domain of scientific inquiry. Each successive theory is held to mark an **advance over its predecessor**.



- **name**: Paul Karl Feyerabend
- **born:** January 13th, 1924, Vienna, Austria
- **died:** February 11th, 1994, Genolier, Vaud, Switzerland
- **fields:** philosophy, science

Feyerabend is well known for his purportedly **anarchistic view of science** and his rejection of the existence of universal methodological rules

Features of methodological monism [7]:

- a demand for increased empirical content (inductive scientific method)
- the forbidding of ad hoc hypotheses
- the principle of falsification (popper)
- the consistency condition (Kuhn)

[7] The doctrine that only one supreme being exists.

Feyerabend demonstrates that **these features imply that science could not progress**, hence an **absurdity** for the proponents of the **scientific method**. Thus:

- There are no universal rules of science
- Truth/meaning is internal to theories
- Freedom superior to truth

1. Observation of phenomena
2. Development of hypothesis to explain observation
3. Development of predictions based on hypothesis
4. Experiments conducted to test predictions
5. Data collection & analysis (data can be numerical, graphical, visual observations, case studies)
6. Modify hypothesis until it is consistent with the observations
7. Derive conclusion

The scientific method - revisited 2

1. Formulate a question
2. Research the question
3. Form a hypothesis
4. Conduct an experiment to test your hypothesis
5. Analyse data
6. Draw conclusions
7. Communicate results

The scientific method - Formulation of question

What do you want to know or explain?

Use **observations** you have made to write a **question** that addresses the problem or topic you want to investigate.

Researching a question allows to know if others have done this same experiment before and if so, what their data suggests. If their conclusion is widely accepted, you may want to try a different angle/perspective or test a different variable.

Also the scientific concepts associated with the experiment should be researched/investigated.

What do you think will happen?

A hypothesis is the prediction for the outcome of the experiment. It is based on observations and should be testable.

Conduct an experiment to test the hypothesis

Design a procedure that tests your hypothesis to see if the prediction is correct.

Record all the data and observations and put them into a neat and organised table and/or in a as self-explanatory as possible chart/schema.

Is your data reliable? Does it make sense?

Place the data into a chart/graph/table and look for any trends/correlation.

Does your data and observations support your hypothesis?

If a definite conclusion cannot be made, the experiment can be performed again. This means the procedure needs to be rewritten because not specific enough or the hypothesis has to be changed.

Report the results of the experiment to let others know what you have learned.

Scientists may want to repeat your procedure to see if they get the same results as you (**replicability**). They may also tweak your experiment a little and have a slightly different focus.

Also, your results may lead to a new question which may lead to another investigation.

This brings everything again back to the first step

The scientific method vs. the engineering method

The scientific method

The engineering method

- Experimental Computer Science
- Modeling
- Theoretical Computer Science
- Computer Simulation

- Information processes: formulate phenomena, explanations, testing
- Experiments: theory testing, exploration

... an experiment can only show the presence of bugs (flows) in a theory, not their absence.
(Edsger Dijkstra)

Scientific methods for Computer Science - modelling

- take a real world phenomena
- create a simplified model with a set of features (believed useful) of the phenomena
- test model and its behaviour
- compare real world phenomena to model's behaviour

Scientific methods for Computer Science - Theoretical CS

- logic and mathematics (axioms, rules)
- conceptualisation, modelling, analysis (data models, algorithm, complexity)
- different levels of abstraction (automata theory)
- efficiency, optimisation (Dijkstra's shortest paths)
- methodologies (iteration, recursion, induction)

- Investigations beyond current experimental capabilities
- Study phenomena and processes that cannot be replicated in laboratories
- Guided by theory and experimental results (feedback loop)

Are you a computer scientist, a computing engineer, or both?

Suggested readings

- Wilson, E. Bright. An Introduction to Scientific Research (McGraw-Hill, 1952).
- Kuhn, Thomas. The Structure of Scientific Revolutions (Univ. of Chicago Press, 1962).
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- Fuller, Steve. Kuhn vs. Popper: The Struggle for the Soul of Science (Revolutions in Science) (Columbia University Press, 2003)
- Gimbel, Steven. Exploring the Scientific Method (Univ. of Chicago Press, 2011).