SC.203 - Scientific Method
Lecture 2 - Introduction to Scientific Method

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Why Scientific Method?

"*An understanding of the scientific method is essential for success and productivity in science*."

Hugh Gauch (2003)

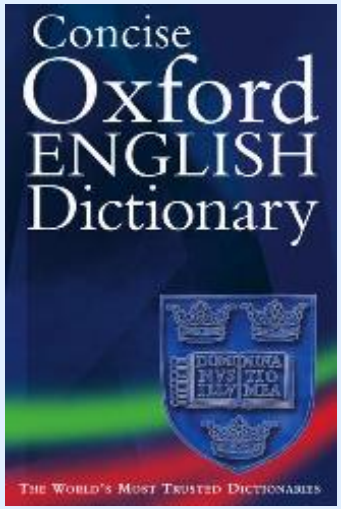
Professor at Cornell University

Scientific Method in Practice

Cambridge University Press

What is Science?

"*A branch of knowledge conducted on objective principles involving the systematized observation of and experiment with phenomena (*facts or occurrences that are perceived*), especially concerned with the material and functions of the physical universe*."



Oxford English Dictionary

What is Science?

Conant, J.B. (*On Understanding Science: An Historical Approach*. New Haven, CT: Yale University Press, 1951) defined science as a connected series of theories and concepts derived from observation and experimentation that can lead to further experimentation and observation.

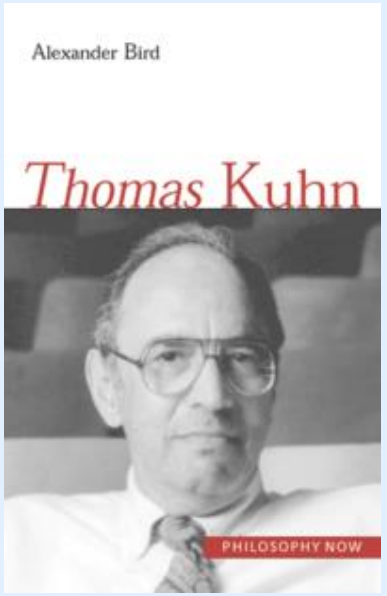
Science, therefore, can be viewed as the process of searching for explanations, or for the causes of events, and it is defined by its method: the **scientific method**.

James Bryant Conant (1893 - 1978) was a chemist, educational administrator, and government official. He was instrumental in the early career of **Thomas Kuhn**, whose ***The Structure of Scientific Revolutions*** has been extremely influential for the various fields of science studies.

What is Science?

"Science is a social activity, which is affected by practical activity, empirical observations and broad theoretical paradigms"

In *The Structure of Scientific Revolutions* (SSR) (1962) Kuhn argued that science does not progress via a linear accumulation of new knowledge, but undergoes periodic revolutions, also called "**paradigm** shifts" (although he did not coin the phrase), in which the nature of scientific inquiry within a particular field is abruptly transformed. In general, science is broken up into three distinct stages. Prescience, which lacks a central paradigm, comes first. This is followed by "normal science", when scientists attempt to enlarge the central paradigm by "puzzle-solving". Thus, the failure of a result to conform to the paradigm is seen not as refuting the paradigm, but as the mistake of the researcher, contra Popper's refutability criterion



Goals of Science

- Discovery of Regularities
  - Description of Phenomena.
  - Discovering Laws. **Law** - a statement that certain events are regularly associated with each other in an orderly way.
  - Search for Causes.
    - We often overlook the real cause,
    - Some events are just coincidences,
    - Sometimes the real cause is another event correlated with the suspected cause,
    - Cause cannot happen after their effects.

Goals of Science

"*The ultimate goal of science is the development of a theory to explain the lawful relationships that exist in a particular field*."

E. Bright Wilson, Jr.
Theodore William Richards Professor of Chemistry, Emeritus, Harvard University

- Development of Theories
  - Theory - A statement or set of statements explaining one or more laws, usually including one indirect concept needed to explain the relationship.
  - Falsifiability - property of a good theory that is capable to disproof. Theory must be testable.
  - Role of Theories: organising knowledge and explaining laws; predicting new laws; guiding research.

Philosophies of Science

"The process of scientific thinking depends both on making careful observations of phenomena and on inventing theories for making sense out of those observations."

(AAAS, 1989)

Ant, Spider, and Bee

Francis Bacon (1561-1626)

"Men of experiment are like the ant, they only collect and use..

The reasoners resemble spiders, who make cobwebs out of their own substance..

But the bee takes the middle course, it gathers its material from the…field, but transforms and digest it by a power of its own"

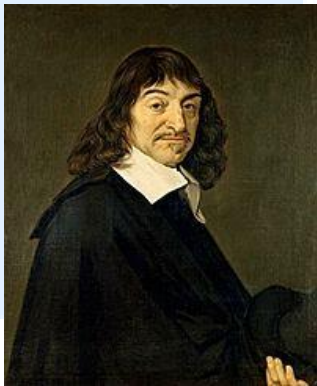
Scientific Method

- Science started with the observation of the nature [1] and by the belief that the observed phenomenon can be explained [2] through an abstraction so-called «*scientific*.» People had thought that sciences could be "*nobler*" if She could explain all phenomena and problems using only one generalized, prescribed procedure.
- For long time, scientists and philosophers had tried to formulate such a procedure, popularly known under the label «***scientific method***.»
- The so-called «*recipe*» had been assumed capable to govern all aspects of scientific research.
- Nowadays, everybody recognize that the process to respond to scientific problems is lots more subtle than a prescribed procedure, recipe, or technique. Sole problem: The Rose [3] !

1. [Martin Goldstein et Inge Goldstein, *How We Know* – Plenum Press 1979 p.19]
2. [W. Beveridge, *The Art of Scientifique Investigation* – W. Norton, 1957, p. 87]
3. [Shakespeare, *Hamlet*, p.?]

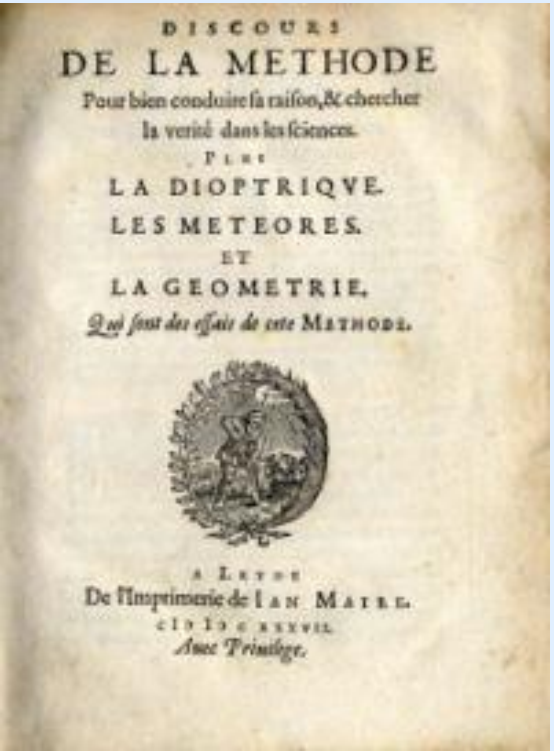
Scientific Method

- The original scientific method, also called *Cartesian Method*, was proposed by Rene Descartes in the XVIIth. Its main tenet was that the entire world could be understood in terms of machines, and its main approach was *divide-and-conquer*:
  1. Analyse: to divide any concept or thing, preferably into 2 parts, and to keep subdividing until reaching “clear and distinct” parts;
  2. Synthesis: to reassemble the parts bottom-up to create a whole; and
  3. Validation: to do an overall audit to ensure the process was used properly.



Scientific Method

- Formal experimental science came later as an outgrowth of the broader Cartesian methods of inquiry.
- Usually, one has to analyze the data collected and come up with a new hypothesis and start the process all over again.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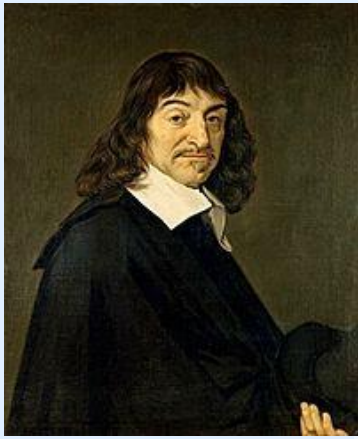


The Discourse on the Method is a philosophical and mathematical treatise published by **René Descartes** in 1637. Its full name is *Discourse on the Method of Rightly Conducting the Reason, and Searching for Truth in the Sciences.* It has beenone of the most influential works in the history of modern science.

Scientific Method

"*Science is a process for:*

- *systematically collecting and recording data about the physical world,*
- *then categorizing and studying that data*
- *to infer the principles of nature that best explain the observed phenomena.*"

Definition agreed by 72 Nobel laureates in 1986 according to www.answersinscience.org/What-Is-Science.htm

Hypothesis in Science

- Hypothesis -
  - A statement that is assumed to be true for the purpose of testing its validity.
  - The statement must be one that is either true or false.
  - A scientific hypothesis must be capable of empirical testing and, as a result, empirical confirmation or disconfirmation.

Scientific Method in Physics

- Scientific Method is a formal method for understanding phenomena. It consists, briefly, of:
  - A description of the phenomena.
  - At least two **hypotheses** which “explain” the phenomena.
  - Extrapolation of the hypotheses until an experiment is found which will distinguish between them.
  - Performance of the experiment, and rejection of one or more hypothesis according to the result.

Scientific Method vs. Programming

- **Scientific Method:**

1. Identify the behaviour you want to explain.
2. Form a Hypothesis that might explain that behaviour.
3. Conduct an experiment that tests the hypothesis.
4. If the experiment contradicts the hypothesis, revise it or replace it with a new hypothesis and go back to step 3.

- **Debugging:**

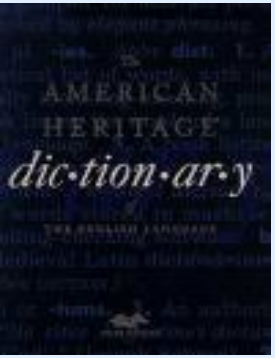
1. Identify the malfunctioning in your program (bug) you want to fix.
2. Make a guess as to what the program is doing to cause the bug.
3. Conduct a test to see if the guess is correct.
4. If the test contradicts the guess than revise it or replace it with a new guess and go back to step 3.

Discussions

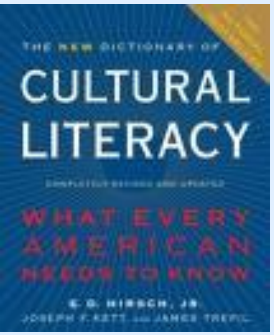
- *Difference between Scientific Method and Debugging:*
  - The scientific method looks at many data points and tries to construct a general theory to cover them; Debugging looks at a single data point.
  - Experiments in scientific method require modelling and simulations to test the hypothesis. Sometimes the contradictions between the experiments and the hypothesis come from the errors in modelling and incompleteness in simulation environments.
  - Other points?

Scientific Method in Dictionaries

Scientific method



"The ***principles and empirical processes of discovery and demonstration*** considered characteristic of or necessary for scientific investigation, generally involving the ***observation of phenomena***, the ***formulation of a hypothesis*** concerning the phenomena, ***experimentation*** to demonstrate the truth of falseness of the hypothesis, and a ***conclusion*** that validates or modifies the hypothesis." (*The American Heritage Dictionary of the English Language, 4th Edition, 2004.)*



"An ***orderly technique of investigation*** that is supposed to account for scientific progress. The method consists of the following steps: (1) careful ***observations*** of nature. (2) ***Deduction*** of natural laws. (3) Formulation of ***hypotheses*** - generalization of those laws to previously unobserved phenomena. (4) Experimentation or ***observational testing*** of the validity of the predictions thus made. Actually, scientific discoveries rarely occur in this idealized, wholly rational, and orderly fashion." (*The New Dictionary of Cultural Literacy, 3rd Edition, E.D. Hirsch, Jr. , J.F. Kett, and J. Trefil, editors 2002.)*

Scientific Method in Wikipedia©

"A scientific method or process is considered fundamental to the scientific investigation and acquisition of new knowledge based upon **physical evidence**.

Scientists use ***observation***, ***hypotheses*** and ***deductions*** to propose ***explanations*** for natural phenomena in the form of *theories*.

Predictions from these theories are tested by **experiment**. If a prediction turns out to be correct, the theory survives. Any theory which is cogent enough to make predictions can then be tested reproducibly in this way.

The method is commonly taken as the ***underlying logic of scientific practice***.

A scientific method is essentially an extremely cautious means of building a supportable, evidence-based understanding of our world."

(Wikipedia information about scientific method, article licensed under the GNU Free Documentation Licence.)

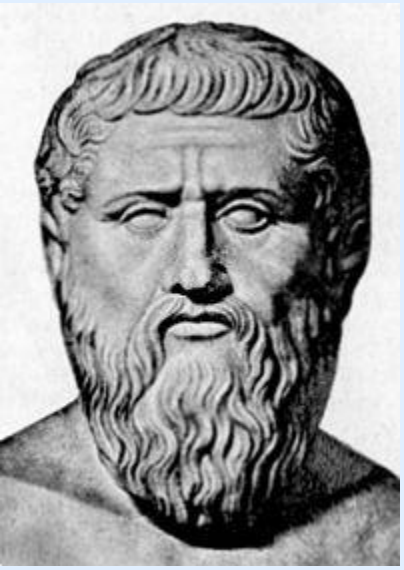
History - Empiricism

The *Edwin Smith Papyrus* (circa 1600 BC) details the examination, diagnosis, treatment and prognosis of numerous ailments.

Evidence of traditional empiricism appears also in the *Ebers papyrus* (circa 1550 BC) that prescribed diseased demons and superstition.

The *Edwin Smith Papyrus* is the world's earliest known medical document, written in hieratic around the 17th century BCE, but thought to be based on material from a thousand years earlier. It is an ancient textbook on trauma surgery, and describes anatomical observations and the examination, diagnosis, treatment, and prognosis of numerous injuries in exquisite detail. (Wikipedia)

History - Plato (428-348 BC)



In Ancient Greece, towards the middle of the Vth century BC, some of the elements of a scientific tradition were already well established.

In *Protagoras*, **Plato** mentions the teaching of arithmetic, astrology and geometry in schools. The philosophical ideas of this time were mostly freed from the constraints of everyday phenomena and common sense. This denial of reality as we experience it reaches an extreme in *Parmenides* that who argued that the world is one and that change and subdivision do not exist.

Plato (Greek: Πλάτων, Plátōn, "wide, broad-browed") (428/427 BC – 348/347 BC), was a Classical Greek philosopher. Together with his teacher, **Socrates**, and his student, **Aristotle**, Plato helped to lay the philosophical foundations of Western culture.

Aristotle (384 - 322 BC) and Empiricism

Aristotle provided yet another ingredient of scientific tradition: ***empiricism***.

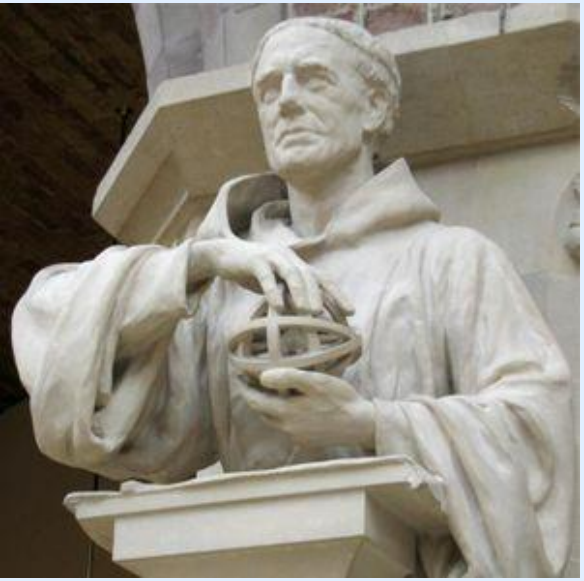
For him, the Platonic, universal ideal is to be found in particular things, what he calls the ***essence*** of things.

Using the concept of essence, Aristotle ***reconciles abstract thought with observation***.

In Aristotelian science, we find the beginnings of a primitive inductive method, although one that is based on collections of objects rather than experimentation.

Aristotle (Greek: Ἀριστοτέλης Aristotélēs) (384 BC – 322 BC) was a Greek philosopher, a student of Plato and teacher of Alexander the Great.

History - Roger Bacon (1214-1294)



Roger Bacon, also known as *Doctor Mirabilis* (Latin: "wonderful teacher"), English philosopher who placed considerable emphasis on empiricism, he was one of the earliest European advocates of the modern scientific method.

In his enunciation of a "*method*" (XIIIth - under dir. Robert Grosseteste and inspired by the writings of the Arab alchemists who had preserved and built upon Aristotle's portrait of induction), described a repeating cycle of *observation, hypothesis, experimentation,* and the need for independent *verification.*

History - Francis Bacon (1561-1626)

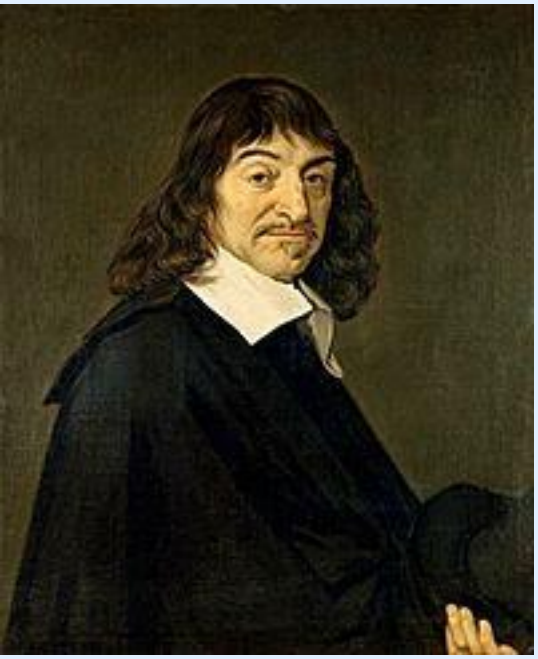
> "***by successive steps***
> ***not interrupted or broken,***
> ***we rise from particular to lesser axioms;***
> ***and then to middle axioms, one above the other;***
> ***and last to all to the most general***."

Francis Bacon in *Novum Organum (1620)* attempted to describe a rational procedure for establishing causation between phenomena.

He argued that scientific theories (or rather *axioms*) should remain as close to the facts as possible.

His method made progress The lesser axiom in this case should be rooted in experience obtained under stringent experimental conditions.

History - Rene Descartes (1596-1650)



- *Rules for the Direction of Mind (1619)* established the framework for a scientific method's guiding principles.
- *Discourse on Method* (1637) presented the four-precepts method:

  "*The first was never to accept anything for true which I did not clearly know to be such; that is to say, carefully to avoid precipitancy and prejudice, and to comprise nothing more in my judgement than what was presented to my mind so clearly and distinctly as to exclude all ground of methodical doubt.*

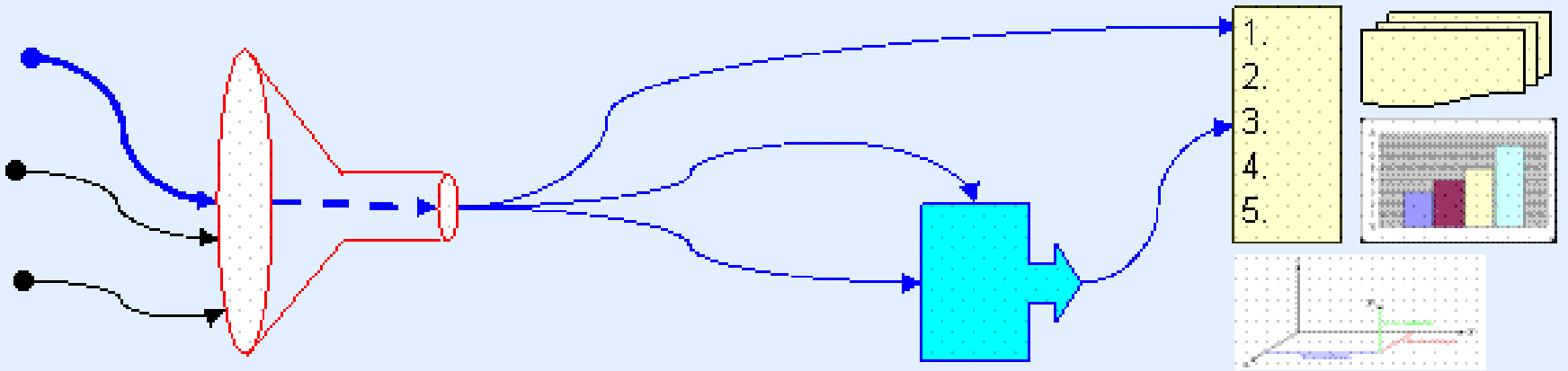
  The second, to divide each of the difficulties under examination into as many parts as possible, and as might be necessary for its adequate solution.

  The third, to conduct my thoughts in such order that , by commencing with objects the simplest and easiest to know, I might ascend little by little, and, as it were, step by step, to the knowledge of the more complex …

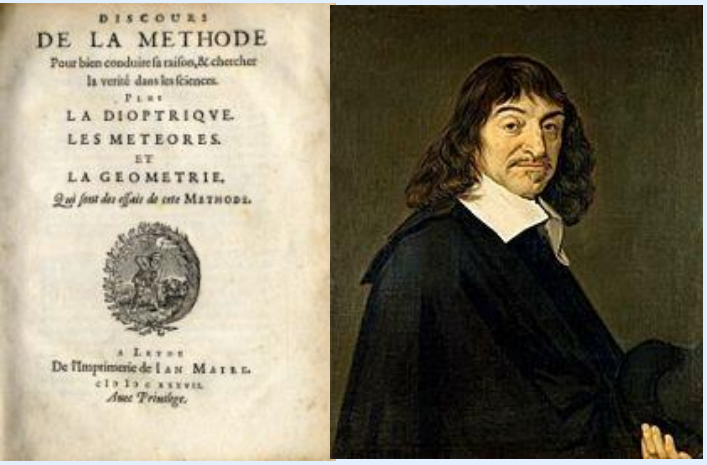
  And the last, in every case, to make enumerations so complete, and reviews so general, that I might be assured that nothing was omitted."

René Descartes (French IPA: [ʁə'ne de'kaʁt]) (March 31, 1596 – February 11, 1650), also known as **Renatus Cartesius** (latinized form), was a highly influential French philosopher, mathematician, scientist, and writer.

The Four Precepts (Descartes)



1. Accept only that which you are sure of	2. Divide into as small parts as necessary	3. Solve the simplest problems first	4. Make as complete lists as possible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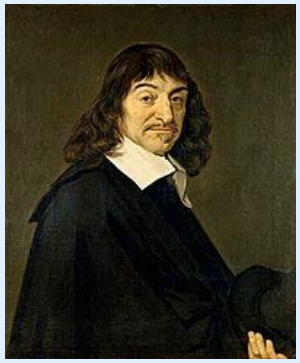
Avec Privilege.

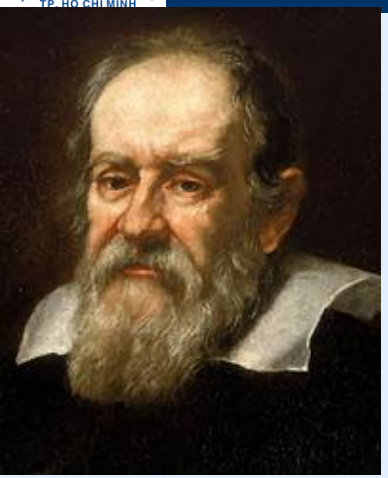
Discussion

- Both Bacon and Descartes wanted to provide a firm foundation for scientific thought that avoided the descriptions of the mind and senses.
- Bacon envisaged that foundation as essentially physical and factual, whereas Descartes trusted to logic and mathematics.

- Are these suffice as foundation for scientific thought?

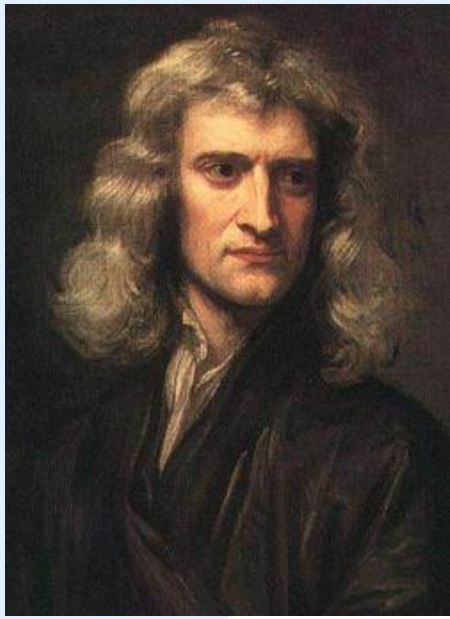


Galileo Galilee and Isaac Newton



Galileo Galilei (1564 –1642) was a Tuscan (Italian) physicist, mathematician, astronomer, and philosopher who played a major role in the scientific revolution.

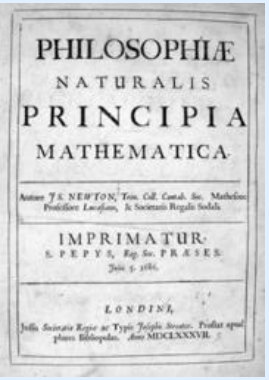
Sir Isaac Newton (/ˈnjuːtən/)(1643 – 1727) was an English physicist, mathematician, astronomer, natural philosopher, and alchemist. His treatise ***Philosophiae Naturalis Principia Mathematica***, published in 1687, described universal gravitation and the three laws of motion, laying the groundwork for classical mechanics, which dominated the scientific view of the physical universe for the next three centuries and is the basis for modern engineering. He showed that the motions of objects on Earth and of celestial bodies are governed by the same set of natural laws by demonstrating the consistency between **Kepler's** laws of planetary motion and his theory of gravitation, thus removing the last doubts about heliocentrism and advancing the scientific revolution.



History - Four Rules of Reasoning

- **Galileo Galilei** combined quantitative experimentation and mathematical analysis to permit the enunciation of general physical laws.

- **Isaac Newton** systematized these laws in the *Principia,* which became a model that other sciences sought to emulate. His four "*Rules of Reasoning*" are:

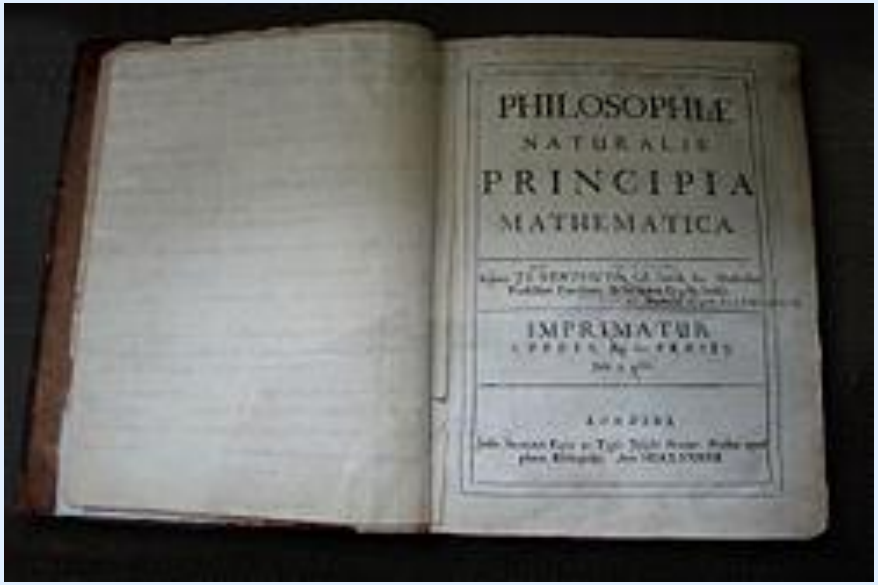

PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA
IMPRIMATUR
LONDINI,

1. *"We are to admit to more causes of natural things than such as are both true and sufficient to explain their appearances.*
2. *Therefore to the same natural effects we must, as far as possible, assign the same causes.*
3. *The qualities of bodies, which admit neither intension nor remission of degrees, and which are found to belong to all bodies within the reach of our experiments, are to be esteemed the universal qualities of all bodies whatsoever.*
4. *In experimental philosophy we are to look upon propositions collected by general induction from phenomena as accurately or very nearly true, notwithstanding any contrary hypotheses that may be imagine, till such time as other phenomena occur, by which they may either be made more accurate, or liable to exceptions."*

Discussion

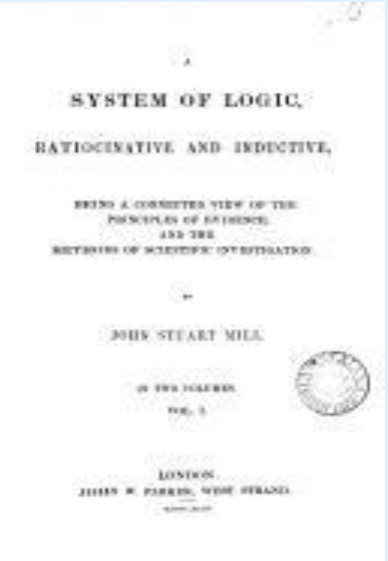
- Why such rules?
- Why Newton also left an admonition about a ***theory of everything:***

  "To explain all nature is too difficult a task for any one man or even for any one age. This is much better to do a little with certainty, and leave the rest for others that come after you, than to explain all things."



History - Principles of Reasoning

- Some methods or reasoning were systematized by **John Stuart Mill**'s *Systems of Logic,* which are five explicit statements of what can be discarded and whet can be kept while building a hypothesis.

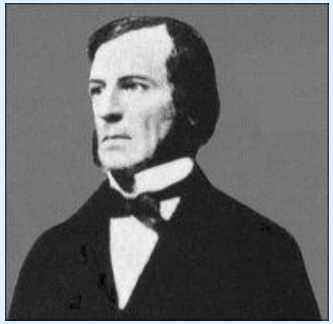

A
SYSTEM OF LOGIC,
RATIOCINATIVE AND INDUCTIVE,
BEING A CONNECTED VIEW OF THE PRINCIPLES OF EVIDENCE, AND THE METHODS OF SCIENTIFIC INVESTIGATION.
JOHN STUART MILL.
LONDON.

Direct Method of agreement
"If two or more instances of the phenomenon under investigation have only one circumstance in common, the circumstance in which alone all the instances agree, is the cause (or effect) of the given phenomenon."
Method of difference
"If an instance in which the phenomenon under investigation occurs, and an instance in which it does not occur, have every circumstance in common save one, that one occurring only in the former; the circumstance in which alone the two instances differ, is the effect, or the cause, or an indispensable part of the cause, of the phenomenon."
Joint method of agreement and difference
Symbolically, the Joint method of agreement and difference can be represented as:
A B C occur together with x y z
A D E occur together with x y w also B C occur with y z
Therefore A is the cause, or the effect, or a part of the cause of x.
Method of residues
If a range of factors are believed to cause a range of phenomena, and we have matched all the factors, except one, with all the phenomena, except one, then the remaining phenomenon can be attributed to the remaining factor.
A B C occur together with x y z
B is known to be the cause of y
C is known to be the cause of z
Therefore A is the cause x.
Method of concomitant variations (with ↑ representing an increase):
A B C occur together with x y z
A↑ B C results in x↑ y z.
Therefore A and x are causally connected

John Stuart Mill (20 May 1806 – 8 May 1873), British philosopher, political economist, civil servant and Member of Parliament, was an influential liberal thinker of the 19th century.

History - Principles of Science

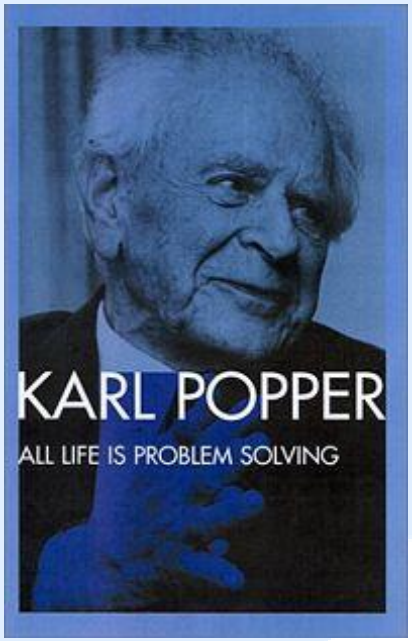
- **George Boole** and **William Stanley Jevons** also wrote on the principles of reasoning (cf. W.S. Jevons, 1874, 1877, *The Principles of Science, 786pp.,* reprinted by Dover, 1958.)
- These attempts to systematize a scientific method were faced with the *Problem of Induction,* which points out that inductive reasoning is not logically valid. **David Hume** set the difficulty out in detail. **Karl Popper** argued that a hypothesis must be ***falsifiable*****.**



Boole (1815-1864)

Jevons (1835-1882)

Hume (1711-1776)



Sir Karl Popper (1902-1994)

No Single "Scientific Method!"

- Difficulties with this have led to**the rejection of the idea that there exists a single method that applies to all science, and that serves to distinguish science from non-science.**

- In the past century, some ***statistical methods*** have been developed, for reasoning in the face of uncertainty, as an outgrowth of *statistical hypothesis-testing* to eliminate error, an echo of the program of Francis Bacon's *Novum Organum.*

The ***Novum Organum*** is a philosophical work by **Francis Bacon** published in 1620. The title translates as ***"new instrument"***. This is a reference to **Aristotle's** work ***Organon*** which was his treatise on logic and syllogism. In *Novum Organum*, **Bacon** details a new **system of logic** he believes to be superior to the old ways of syllogism. For Bacon, finding the essence of a thing was a simple process of reduction. In finding the cause of a phenomenal nature such as heat, one must list all of the situations where heat is found. Then another list should be drawn up, listing situations that are similar to those of the first list except for the lack of heat. A third table lists situations where heat can vary. The form nature, or cause, of heat must be that which is common to all instances in the first table, is lacking from all instances of the second table and varies by degree in instances of the third table.

Mathematical vs. Scientific Method

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

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

George Pólya (1887 –1985)

Confusing enough?

- If you are not confused by what is:
  - Science?
  - Scientific Method?
  - History of Science and Scientific Method?
  - Philosophy of Science?

Then we'd need to restart again!

Else,

- Go to the next slide.

Assignments

- **Understandings:**
  - Summarize article on “Scientific Method” in Wikipedia http://en.wikipedia.org/wiki/Scientific_method (max 2 pages).