The scientific method

The scientific method is the collection of techniques that scientists use to investigate phenomena and gain knowledge about the universe.
The way science is developed and the techniques employed to obtain new knowledge change from field to field. However, central to the scientific method are the ideas of 'trial and error', verifiable and reproducible results and the ability of making predictions on the future outcomes of experiments and observations.

Difference between knowledge and belief:
A belief is an internal thought or memory which exists in one's mind. Sometimes beliefs become knowledge. Most people accept that for a belief to be knowledge it must be, at least, verified and justified.

Types of knowledge:
What does it mean to know something? There are several kinds of knowledge. For example to know that massive bodies fall towards the ground is different from knowing how massive bodies interact. Knowledge about things (comprehension, theoretical) is different from knowledge from direct acquaintance (apprehension, empirical). The knowledge that we derive from mathematics is different from the knowledge we derive from experience. For example, by studying the laws of Physics, I can learn that the surface of a star like the Sun has a temperature of 6,000°K (comprehension). On the other hand, I learn how to hit a forehand in tennis by repeating the action several times over and over (apprehension).

- **A priori** knowledge (inferential) deals with necessary conclusions from first premises. A priori knowledge is independent of experience, as with mathematics (3+2=5), tautologies and deduction from pure reason (ontological proofs).
- **A posteriori** knowledge (empirical) deals with conclusions based on observations. A posteriori knowledge is dependent on experience or empirical evidence, as with most aspects of empirical science and personal knowledge.

Ad hoc hypothesis vs. scientific hypothesis:
- A hypothesis (plural *hypotheses*) is a proposed explanation for a phenomenon.
  - Ad hoc is a Latin phrase meaning 'for this'. In science and philosophy, ad hoc means the addition of further concepts to a theory to save it from being falsified. Ad hoc hypotheses compensate for anomalies not anticipated by the theory in its unmodified form. Scientists are skeptical of theories that rely on unsupported adjustments to sustain them. However ad hoc hypotheses are not necessarily incorrect.
  - For a hypothesis to be scientific it must be testable. Scientists generally base scientific hypotheses on previous observations that cannot satisfactorily be explained with the available scientific theories.
- **Occam's razor**: Occam's razor (also written as Ockham's razor, and *lex parsimoniae* in Latin, which means law of parsimony) is a problem-solving

principle attributed to William of Ockham (c. 1287–1347). The principle can be interpreted as stating ‘Among competing hypotheses, the one with the fewest assumptions should be selected’.

Example: In order to explain the apparent motion of planets within a geocentric model of the solar system, astronomers introduced the idea of epicycles. The introduction of epicycles is an ad hoc hypothesis that allows to explain observations. However the heliocentric model of the solar system explains observations with a smaller number of assumptions and it is thus preferable (Occam’s razor).

Scientific knowledge:

One of the great advantages of science is its ability to produce new knowledge based on previous knowledge. Another advantage is the ability to make (quantitative) predictions.

Example: Ancient humans that could predict when spring would come had a better chance of survival with respect to those that couldn’t. Therefore the importance of looking at the sky and understanding the periodic character of the motion of the stars and its relation to the change of seasons.

We observe that every 365 days the Sun occupies the same position in the sky at noon. An ad hoc hypothesis to explain this observation is: “There is an invisible chariot driven by an invisible powerful creature that brings the Sun back and forth in the sky.” This hypothesis can not be tested and does not make any predictions.

A scientific hypothesis is: “The apparent position of the Sun is determined by the motion of the Earth around it. The Earth moves on an elliptical orbit and follows the mathematical laws developed by Kepler.” This hypothesis can be tested (‘as a consequence of the specific motion of the Earth stars will have specific positions in the sky’, which can be observed to confirm the hypothesis) and it makes predictions (‘on this day the Sun will have this position in the sky at noon’).

Example: In maritime battles being able to predict where the cannon balls would land gave an advantage over the enemies who were shooting randomly. Therefore the importance of a quantitative theory for the motion of massive bodies in the gravitational field of the Earth.

Other forms of knowledge do not have the same advantage. It is this advantage that allows to predict events in the future (e.g. eclipses, weather forecast) and develop new knowledge and technology.

Cosmological principle:

One fundamental assumption of science is that we do not occupy a special place in the universe. The cosmological principle is usually stated as 'Viewed on a sufficiently large scale, the properties of the universe are the same for all observers.' This amounts to the philosophical statement that the part of the universe which we can see is a fair sample, and that the same physical laws apply throughout. It was already stated by Newton in the book “Philosophiæ Naturalis Principia Mathematica” where the laws of gravitation was described.

The principle is related to the idea that the laws of physics that we use to describe the universe do not depend on the observer’s position in space and time.

The results on an experiment or observation carried out on Earth or on a distant planet in another galaxy should rely on the same theoretical model. The results of an experiment or observation carried out today or in the distant future should rely on the same theoretical model. This is not entirely true, as the universe evolves its structures and conditions change. Nevertheless knowing the laws by which the universe evolves allows us to make predictions for experiments and observations that can ideally be carried out at any point in space and any time in the history of the universe.

The scientific method:
The scientific method is a body of techniques for investigating phenomena, acquiring new knowledge, or correcting and integrating previous knowledge. To be termed scientific, a method of inquiry should be based on empirical or measurable evidence subject to specific principles of reasoning. The scientific method is an ongoing process, which usually begins with observations about the natural world. The best hypotheses lead to predictions that can be tested in various ways, including making further observations about nature. In general, the strongest tests of hypotheses come from carefully controlled and replicated experiments that gather empirical data. Depending on how well the tests match the predictions, the original hypothesis may require refinement, alteration, expansion or rejection. If a particular hypothesis becomes very well supported a general theory may be developed.

Scientific theories have a limited range of applicability, they are not 'true', they are an approximate model of reality that works well in a certain context. For example gravity is well described by Newton's theory. In order to send men on the Moon scientists do not need anything more than Newtonian mechanics. Nevertheless Newton's theory is not 'true', since we know now that it fails to describe gravity in certain conditions (like near extremely massive objects or when speed approaches the speed of light).

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.

- **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?'
- **Hypothesis:** A hypothesis is a conjecture, based on knowledge obtained while formulating the question, that may explain the observed behavior of a part of our universe. The hypothesis might be very specific (for example, Einstein's equivalence principle) or it might be broad (for example, unknown species of life dwell in the unexplored depths of the oceans). A scientific hypothesis must be falsifiable, meaning that one can identify a possible outcome of an experiment or observation that conflicts with predictions deduced from the hypothesis; otherwise, it cannot be meaningfully tested ('ad hoc' hypothesis are often not falsifiable).

- **Prediction:** Predictions are obtained by determining the logical consequences of the hypothesis. Ideally, the prediction must 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 (Einstein's theory of gravity and Newton's theory make slightly different predictions for the motion of Mercury).
- **Testing:** This is an investigation of whether the real world behaves as predicted by the hypothesis. Scientists test hypotheses by conducting experiments or making observations. The purpose of an experiment is to determine whether data gathered from 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. Experiments should be designed to minimize possible errors, especially through the use of appropriate scientific controls. Furthermore, failure of an experiment does not necessarily mean the hypothesis is false, as often not all elements that determine the outcome of the experiment can be controlled.
- **Analysis:** This involves determining what the results of the experiment show. In cases where an experiment is repeated many times, a statistical analysis 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.

Other important elements in scientific research are:

- **Replication:** If an experiment cannot be repeated to produce the same results, this implies that the original results might have been in error.
- **External review:** The process of peer review involves evaluation of the work by experts, who typically give their opinions anonymously. Peer review does not certify correctness of the results, only that, in the opinion of the reviewer, the works themselves were sound.
- **Data recording and sharing:** Scientists typically are careful in recording their data. Though not typically required, they might supply this data to other scientists who wish to replicate their original results.

Two ways of constructing a view of the world:

- Bottom up (fitting data). Also called **deductive method**. Scientists collect data and use it to construct a theory. Example: Kepler's laws.
- Top down (checking theories). Also called **inductive method**. Scientists postulate a theory and then devise experiments to check its validity. Example: Newton's law of gravitation.
- The deductive method is a posteriori, as the theory is built from empirical data. On the other hand the inductive method is a priori, as the theory is postulated and data is used afterwards to validate it.

Galileo Galilei (1564-1642):

- In the “Dialogue concerning the two chief world systems” (1632), Galileo compares the Copernican system (with the Sun at the center of the solar system) and the Ptolemaic system (with the Earth at the center). The book is in the form of a series of discussions between two philosophers and a layman.
- While discussing the motion of the Earth in space he introduces the concept of ‘thought experiment’, an experiment that is performed only with imagination. In this particular thought experiment a man who is below deck in a ship cannot tell whether the ship is moving or not.
- In the “Dialogue” he writes: “Philosophy is written in that great book which ever is before our eyes - I mean the universe - but we cannot understand it if we do not first learn the language and grasp the symbols in which it is written. The book is written in mathematical language, and the symbols are triangles, circles and other geometrical figures, without whose help it is impossible to comprehend a single word of it; without which one wanders in vain through a dark labyrinth.”

Cause and effect:

- Causality (or cause and effect) is what connects one process (the *cause*) with another process or state (the *effect*), where the first is understood to be (partly) responsible for the second, and the second is dependent on the first. Causes always precede their dependent effects.
- For science the assumption that any observable effect must follow uniquely from one or more causes allows to build testable models of how things work. Also it is important to assume that from similar causes follow similar effects.
- For example in classical mechanics we assume that bodies obey Newton’s law of gravitation. Then if we know the force acting on a body and we know the initial position and velocity of the body we can calculate its position and velocity at any time.

The problem of the inductive method:

- Formulated by David Hume (1711-1776), the problem of induction is the philosophical question of whether inductive reasoning leads to knowledge since it relies on unjustified processes such as:
    - Generalizing about the properties of a class of objects based on some number of observations (empiricism) of particular instances of that class.
    - Presupposing that a sequence of events in the future will occur as it always has in the past.
- Example: The fact that all observed crows are black does not imply that every crow must be black.
- Example: The fact that the laws of mechanics have always been observed to hold does not imply that they will hold forever. Or the fact that the sun did rise in the sky every day in the past does not allow us to say for sure that it will also rise tomorrow.
- Newtonian mechanics was so successful that philosophers believed it described the true nature of gravity. Nevertheless, like any scientific theory, we now know that it is just a model that describes gravity well enough under certain

circumstances. Immanuel Kant (1724-1804) wrote the "Critique of pure reason" (1781) to defend Newtonian mechanics from the criticism coming from the problem of induction.

- In 1934 Karl Popper (1902-1994) wrote "The logic of scientific discovery", in which the principles of **falsificationism** are outlined. Scientific theories can only be falsified. We can never hope to verify a theory, in other words, no scientific theory can be proven 'true'. Every theory must be tested to check its domain of validity and may eventually be falsified.
- The basic idea of falsificationism is that while there is no way to prove that the sun will rise tomorrow, it is possible to formulate the theory that every day the sun will rise; if it does not rise on some particular day, the theory will be falsified and will have to be replaced by a different one. As long as the sun rises the theory holds and there is no need to replace it.
- As a consequence we now believe that the experiments that are more useful to science are those aimed as falsifying a theory, rather than those aimed at confirming it.

How new theories are formulated:

- It is generally believed that scientific knowledge is like a building that is constructed, brick after brick, from the foundations upwards. Normal scientific progress is usually viewed as 'development-by-accumulation' of accepted facts and theories. Even though it is true that scientific knowledge is cumulative scientific theories do not get refined better and better, they are falsified and replaced by other theories. The new theory must be able to explain all the phenomena that was explained in the old theory. In addition the new theory must be able to explain something that the old theory couldn't and/or must predict some new phenomena.
- Example: Newton's law of gravitation cannot be refined. Its range of applicability is fixed and in order to describe the motion of massive bodies with speed close to the speed of light we need a new theory (relativity).
- Thomas Khun (1922-1996) in "The Structure of Scientific Revolutions" (1962) argued that the discovery of 'anomalies' during revolutions in science leads to new paradigms. New paradigms require new frameworks and put old questions in a different light. New paradigms then ask new questions of old data, move beyond the mere 'puzzle-solving' of the previous paradigm and change the rules of the game.

Further readings:
[1] Galileo Galilei - Dialogue concerning the two chief world systems (1632).
[2] René Descartes - Discourse on the method (1637).
[3] Isaac Newton - Philosophiæ Naturalis Principia Mathematica (1687).
[4] Immanuel Kant - Critique of pure reason (1781).
[5] Karl Popper - The logic of scientific discovery (1934).
[6] Thomas Kuhn - The Structure of Scientific Revolutions (1962).
[Source: Part of the above material is taken from wikipedia and has been integrated and elaborated to fit the needs of the course.]

The Scientific Method as an Ongoing Process