The scientific method

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Abstract

We present in this article a possible definition of the modern scientific method.

What is the scientific method? There are many definitions out there, but I am providing mine, the one I explain to my students, here in this essay.

SCIENTIFIC METHOD

A (cyclical, iterative, systematic) method/procedure to acquire, gather, organize, check (verify or refute) and test, conserve (preserve) and transmit (communicate) knowledge (both in form of data or organized abstract data/axioms/propositions) or more generally information built from reason and thought.

It is based on the will to know due to ***curiosity*** and it uses:

- Experience. By experience we understand observation of natural phenomena, original thoughts, common sense perceptions and observed data from instruments or data. You can also gather data with emulation or simulation of known data, in a virtual environtment.

- Intuition and imagination. Sometimes scientific ideas come from experience, sometimes from intuitions and abstractions from real world and/or structures. You can also use imagination to test something via gedanken or thought experiments tied to the previous experiences or new experiences, or use computer/AI/machines to creatively check or do inferences.

- Logic and mathematical language. Logic, both inductive and deductive, is necessary for mathematical or scientific proofs. Since Galileo, we already know that Mathematics is the language in which Nature is better described with. We can also say that this includes reasoning or reason as a consequence. Thought and reason are a main tool of Science.

The will to know is basic for scientists. No curiosity, no new experiments, observations, theories or ideas.

The scientific method has some powerful additional tools:

- Computers and numerical simulations. This is new from the 20th century. Now, we can be aided by computer calculations and simulations to check scientific hypothesis or theories. Machine learning (and AI, Artificial Intelligenge) is also included here as subtool.

- Statistics and data analysis. Today, in the era of Big Data and the Rise of AI, this branch and tool from the scientific method gains new importance.

- Experimental devices to measure quantities predicted or expected from observations and or hypotheses, theories or models.

- Rigor. Very important for scientists, and mathematicians even more, is the rigor of the method and analysis.

- Scientific communication, both specialized and plain for everyone. Scientists must communicate and transmit their results and findings for further testing. Furthermore, they must try to make accessible the uses of their findings or why they are going to be useful or not in the future.

Scientific method can begin from data (observations, previous data), or from theories and models. Key ideas are:

- (Scientific) Hypothesis. Idea, proposition, argument or observation that can be tested in any experiment. By experiment, here, we understand also computer simulations, numerical analysis, observation with telescope or data analysis instruments, machine/robotic testing, automatic check and/or formal proof by mathematical induction or deduction.
- An axiom is a statement that is assumed to be true without any proof, based on logical arguments or experience.
- A theory is a set of tested hypotheses subject to be proven before it is considered to be true or false. A theory is also a set of statements that is developed through a process of continued abstractions and experiments. A theory is aimed at a generalized statement or also aimed at explaining a phenomenon.
- A model is a purposeful representation of reality.
- A conjecture is proposition based on inconclusive grounds, and sometimes can not be fully tested.
- A paradigm (Kuhn) is a distinct set of concepts or thought patterns, including theories, research methods, postulates, and standards for what constitutes legitimate contributions to a field.

What properties allow us to say something is scientific and something is not? Philosophy of science is old and some people thought about this question. Some partial answers are known:

- Falsifiability. Any scientific idea or hypothesis or proposition can be refuted and tested. Otherwise is not science. It is a belief. Scientific stuff can be refutable and argued against with. Experiments or proof can be done to check them. Kuhn defended the addition of additional ad hoc hypotheses to sustain a paradigm, Popper gave up this approach.

- Verification of data or hypotheses/theories/arguments. Even when you can refute and prove a theory is wrong, verification of current theories or hypotheses is an important part of scientific instruments.

- Algorithmic truths and/or logical procedures.Science proceeds with algorithms and/or logic to test things. Unordered checking looses credibility. Trial and error is other basic procedure of Science.

- Heuristics arguments based on logic and/or observations. Intuition and imagination can provide access to scientific truths before testing.

- Reproducibility. Any experiment or observation, in order to be scientific, should be reproducible.

- Testable predictions. Usually, theories or hypotheses provide new predictions, not observed before.

The scientific method is an iterative, cyclical process through which information is continually revised. Thus, it can be thought as a set of 4 ingredients as well:

- 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).

Pierce distinguished between three types of procedures:

- Abduction. It is a mere "guess", intuitive and not too formal.

- Deduction. It includes premises, explanations and demonstrations.
- Induction. A set of classification, probations and sentient reasoning.

From a pure mathematical and theorist way, there are only knowing and understanding facts, analysis, synthesis and reviews or extensions of information/knowledge. From the physical or experimentalist viewpoint, however, we have more:

- Characterization of experiences and observations.
- Proposals of hypotheses.
- Deductions and predictions from hypotheses.
- Realization of tests and experiments (gathering data).

Note that, from a simple viewpoint, the scientific method and/or main task of Science is to study:

- Regularities, patterns and relationships between objects and magnitudes.
- Anomalies or oddities, generally hinting something new beyond standard theories.
- Reality as something we measure and the link between observers and that reality.
- What is reality after all? Hard question from the quantum realm side...

By the other hand, a purely bayesianist approach to Science is also possible. In a Bayesian setting, Science is only a set up to test the degree of belief of any proposition/idea/set of hypotheses/model/theory. Theories provide measurable observables and quantities, and scientific predictions are only valid up to certain confidence level with respect some probabilistic distributions. This probabilistic approach to Science does not exclude the existence of purely true or false hypotheses, a frequentist approach to data and error analysis (it complements that tool), and it only focuses on a framework to estimate the probability of propositions, data vectors and experimental parameters fitting certain probability distributions "a prior".

How to elucidate the degree of (scientific) belief of something? W. K. Clifford discussed this topic with Jaynes in order to give a list. In the Ethics of Belief was argued that: rules or standards that properly govern responsible belief-formation and the pursuit of intellectual excellence are what philosophers call epistemic (or "doxastic") norms. Widely accepted epistemic norms include:

1. Don't believe on insufficient evidence.
2. Proportion your beliefs to the strength of the evidence.
3. Don't ignore or dismiss relevant evidence.
4. Be willing to revise your beliefs in light of new evidence.
5. Avoid wishful thinking.
6. Be open-minded and fair-minded.
7. Be wary of beliefs that align with your self-interest.
8. Admit how little you know.
9. Be alert to egocentrism, prejudice, and other mental biases.
10. Be careful to draw logical conclusions.
11. Base your beliefs on credible, well-substantiated evidence.
12. Be consistent.
13. Be curious and passionate in the pursuit of knowledge.

14. Think clearly and precisely.
15. Carefully investigate claims that concern you.
16. Actively seek out views that differ from your own.
17. Be grateful for constructive criticisms.
18. Question your assumptions.
19. Think about the implications of your beliefs.
20. Persevere through boring or difficult intellectual tasks.
21. Be thorough in your intellectual work.
22. Stick up for your beliefs, even in the face of peer pressure, ridicule, or intolerance.

Unanswered questions by Science are yet to be provided:

- Why mathematics is so accurate and precise to describe Nature?
- Why is the Universe comprehensible and non-chaotic but regular and structured in general? It could have been very different!
- Why numbers and structures are so efficient?
- Is Science affected by the Gdel theorems or does it go beyond its applicability?
- Can Science explain everything?
- Are chaos and other mathematical universes possible and physically realizable or ideally are only unfeasible?

Usually, the scientific method contained theory and experiment only. Now, it also includes: computation, big data, machine learning and AI tools!

A shorter 3 step version of the scientific method is the following:

- S1: Make observations, ask questions about them, and gather information.
- S2: Form hypotheses to describe what has been observed, and make predictions.
- S3: Test the predictions against known or new observations, and accept, reject, or modify the hypothesis accordingly.