Science and
Scientific Reasoning

Critical Thinking

Some Common Myths About Science

Science:
What it is and what it is not

Science and Technology

- Science is *not* the same as technology
  - The goal of science is to come to an understanding of the world around us. The products of science are theories about nature.
  - The goal of technology is to help us accomplish something. The products of technology are tools.
- Science and technology have a close relationship:
  - Technology *applies* the knowledge given by science.
  - Scientific research may be driven by technological needs or desires.
- ‘Popular Science’ magazine should really be called ‘Popular Technological Gadgets’

Science and Scientific Theories

- Science is *not* a set of scientific theories
  - Science is like philosophy (in fact, science grew out of that branch of philosophy that studied nature and was called “natural philosophy” until mid-19th century): it is a method, study, investigation, or inquiry.
  - Science can’t be wrong, as science makes no claims.
  - Scientific *theories* are like *philosophies*: they are sets of beliefs. Scientific theories can be wrong.
- Science is the process of figuring out which theories are more likely than others.
  - Who refutes scientific theories? Science itself!

Science and Scientific Experiments

- Science is *not* doing scientific experiments using multi-million dollar equipment
  - First of all, many scientific experiments can be done without any equipment at all.
  - Second, doing scientific experiments is only that part of science where a scientific theory is actually being tested. Scientists first have to come up with a theory to be tested, have to think of a useful test, and have to draw conclusions from the results of that test.
- Many ‘scientists’ are really ‘technicians’.

Science and Math

- Science is *not* a bunch of equations.
- To many people: science = numbers = truth
- Just because we are dealing with a number, doesn’t mean that that number is accurate (and remember: precision is not the same as accuracy).
- And, again, science is so much more than just numbers and equations: it is the process that provided those numbers and equations!

Science and Truth

- Finally, science does *not* have a stronghold on the truth.
  - In fact, it is quite the opposite. Scientists are critical of every theory that they propose: that is why they are constantly being tested. Indeed, this inherent self-reflection, self-modification, and self-correction is what really defines science.
- Science is critical thinking!

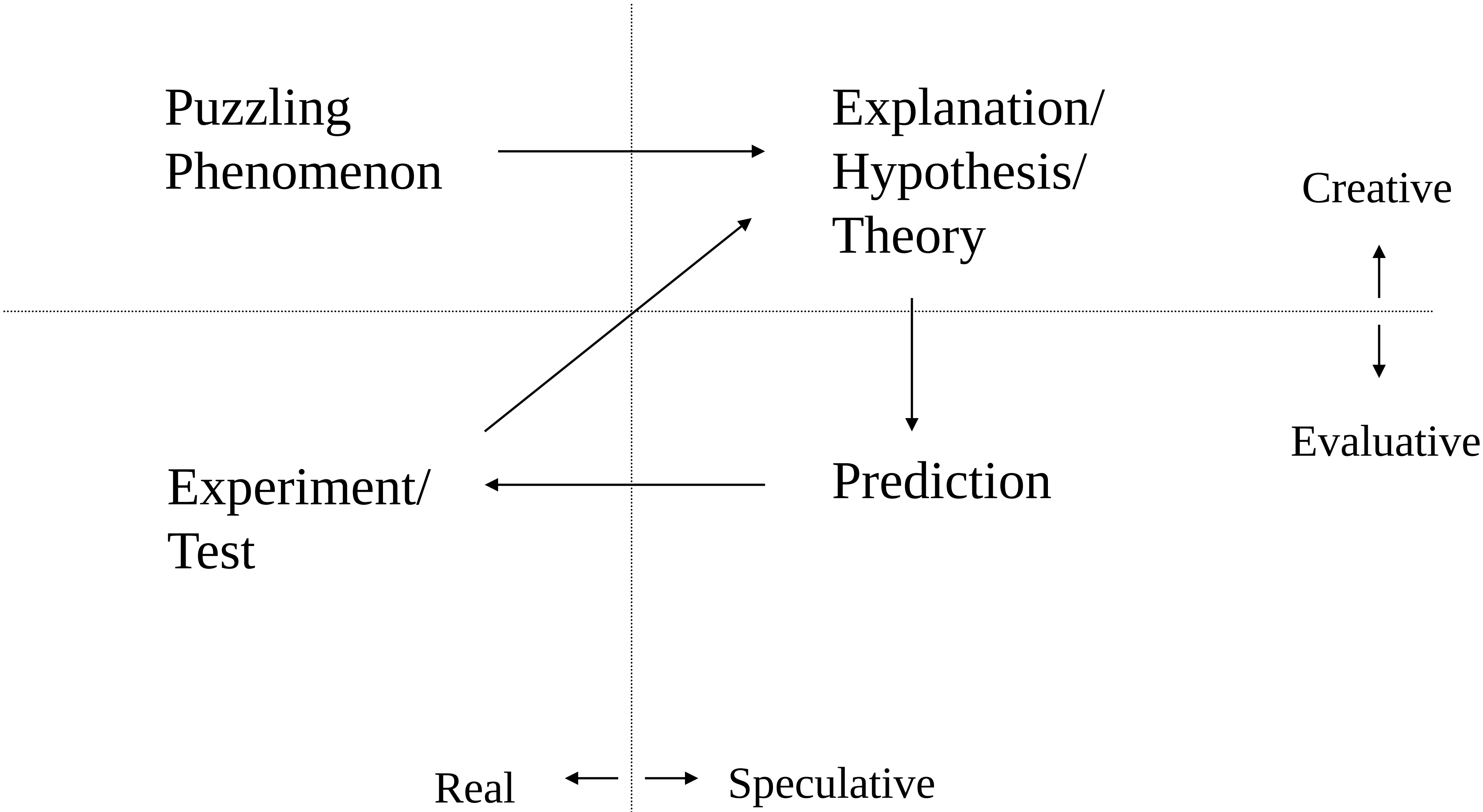
‘Hard’ Science and ‘Soft’ Science

- Fields like physics and chemistry are often referred to as the ‘hard’ sciences, where something like psychology or sociology are ‘soft sciences’.
- Moreover, the ‘hard’ sciences are often seen as ‘more’ scientific than the ‘soft’ sciences
  - Indeed, physics is often seen as the ‘epitome’ of science.
- Now, it is certainly true that the results from physics and chemistry are more quantitative and allow for more reliable explanations and predictions … but that doesn’t make them more scientific!
  - That merely reflects the ‘science = math’ and ‘science = truth’ mindset.

The Scientific Method

Understanding How Science Works
and What It All Means

The Scientific Method



Puzzling Phenomenon

- Many people see science as something that collects data and generalizes from that. However, science doesn’t collect data for the heck of it. Rather, science starts at the moment that we observe something that puzzles us: something for which we want an explanation.

Hypothesis

- The second step of the scientific process is to come up with a possible explanation for the puzzling phenomenon. This explanation is also called a hypothesis or theory.
- Obviously, every proposed theory should explain that what we want to have explained. However, that is not enough to be considered a good theory. Thus we come to the testing phase: prediction and experiment.

Prediction

- In order to test a theory, you need to make a prediction based on the assumed truth of that theory. Thus, in the third step, you consider what would have to be the case if the theory were true.
- The prediction should be novel in that it should predict something that we don’t already know.
- A prediction should also be as specific/precise as possible.

Eliminating Alternative Theories: The Surprise Principle

- The strength of any theory depends largely on how many alternative theories there are: the fewer alternative theories, the stronger the proposed theory. A good prediction is therefore one that is predicted by only few alternative theories, because that way, if the prediction comes out true, we would have strong evidence for the proposed theory, Thus, the more ‘surprising’ it would be that the prediction would come out true, the better. Science can therefore be seen as a process of eliminating bad theories.

Experiment

- The experiment is where we see if the prediction comes out true. That is, predictions often take the form "If you were to do this, then that would happen". In the experiment, we do exactly 'this', and see if 'that' indeed happens.
- Sometimes the 'experiment' consists of a single and simple observation. Again, much of science does not need multi-million $ equipment.

Evidence for a Theory

- A theory is *confirmed* by an experiment if the prediction comes out true.
  - Confirmation doesn’t mean proof, because other theories could have made the same prediction. Thus, we call this *evidence*.
  - Further testing is needed to choose between competing explanations.

Evidence against a Theory

- A theory is *disconfirmed* by an experiment if the prediction comes out false.
  - Disconfirmation does not necessarily mean that the theory is false, as the prediction often relies on *auxiliary hypotheses*. Example: Ships disappearing at the horizon only disproves the Flat Earth Hypothesis if light travels in a straight line.
  - Disconfirmation of a theory can lead to either *rejection* or *modification* of that theory. In fact, even if a theory is false, it could still represent a useful *approximation*. Example: Newton's laws.

Scientific Reasoning

- When doing science, we use all kinds of reasoning. For example, when we make a prediction, we probably use deductive reasoning. And when we generalize from certain data, we use inductive reasoning. However, the core reasoning in science is called abductive reasoning (or hypothetical reasoning): we reason what, given the facts, would best explain those facts. Sometimes scientific reasoning is therefore called "inference to the best explanation".

Data and Theories

- Scientific theories are driven by data, not vice versa. That is, science will adjust its theory according to the available data, rather than trying to find data that is compatible with a given theory. To put it yet another way: the theory should fit the data, rather than that the data should fit the theory. Again, science tries to make a theory by trying to break it, rather than by selectively picking and choosing data to confirm whatever theory at hand.

Scientific ‘Proof’

- Scientists are critical of their own theories, because they know that every proposed theory can be false: no amount of evidence can prove a theory with 100 percent certainty.
- So, what then does it mean for a theory to be “scientifically proven”? It means that there is so much evidence for that theory that the truth of that theory is put beyond “reasonable” doubt.

Proof: from L. *probare* "to test”

- Using predictions, we put a theory to the test. And, we put the theory to the test as hard as we can by considering the most unlikely predictions. This critical process is what used to be called ‘proving a theory’. That is, when you prove a theory, you are very critical of it, and put some strain on it. The saying “the exception proves the rule” uses this old meaning of the word ‘proof’.
- Nowadays, ‘proof’ means something that supports our theory, rather than something that puts strain on it: almost the opposite! (although you can think about it this way: by proving (testing) a theory, we may end up giving support for it (if the theory passes the proof of course!)).
- This change in meaning is rather unfortunate, because while the goal of science is to come up with true theories, its method is to put as much strain on a theory as possible. So yes, science is proving theories, but really in the old sense of the word!

Provisional Acceptance

- Q: Given that science can’t conclusive prove anything, why should I accept any kind of scientific theory?
- A: Am I certain to die if I jump off a cliff? No, but I wouldn’t count on the possibility of not dying! The same goes for scientific theories: as long as there is evidence for them, you have reason to believe that they are true rather than false. And remember, you should never blindly accept any theory anyway. You should believe it to the degree that there is evidence for it. Thus, it is ok to accept scientific theories, as long as you do so provisionally, and are ready to change it for a better theory if the evidence points in a different direction.
- Note: Sometimes people say: “It’s just a theory”, implying that that particular theory can be ignored, or at least its importance downplayed. Again however, while no theory is conclusive, this does not mean that we can ignore them.

Criteria of Adequacy

What Makes for Good Scientific Theories, Hypotheses, and Explanations

Criteria of Adequacy

- The purpose of theories, hypotheses, and explanations in general, is to help us understand something and (thus) to enable to help us make reliable predictions about that something.
- The criteria of adequacy help us evaluate whether a suggested explanation has the *potential* to fulfill this purpose.
- An explanation that satisfies all criteria of adequacy is called a *proper* explanation.

Criteria of Adequacy and Fallacies

- There is an interesting parallel between criteria of adequacy and fallacies:
  - A proper argument does not commit any fallacy, but an argument that does not commit any fallacy may still be an argument with a false conclusion.
  - A proper explanation does not violate any criteria of adequacy; but an explanation that does not violate any criteria may still be wrong.
- Thus: Criteria of adequacy are the *minimal* properties that a good explanation should have.

Relevance

- At the very least, explanations should be a possible explanation of that what it is that it is supposed to explain.
- *Explanandum*: that which needs to be explained
- *Explanans*: the suggested explanation
- The explanandum should *follow from* the explanans.

Non-Circularity

- Explanations should not be circular. A circular explanation merely restates (using different words) what needs to be explained.
- Circular explanations don’t increase our understanding; they don’t provide us with any insights into what we want to understand.
- *Virtus Dormitiva*: “Opium puts you to sleep, since opium has sleep-inducing powers.”

Testability / Refutability

- Theories should be testable …
  - If a theory cannot be tested, then we can’t confirm it.
  - So, we can’t give reasons to believe its truth either.
  - Hence, we can’t justify that the explanation increases our understanding or predictive powers.
  - Thus, any untestable theory is a bad theory.
- Therefore, theories should be refutable!
  - There must be a possible way of refuting the theory, i.e. we should be able to disconfirm the hypothesis.
  - For if we can’t disconfirm the hypothesis, then we can’t possibly confirm the hypothesis either.

Generality / Simplicity

- A sign of a good theory is that it is general:
  - It can explain many things
  - Even better: it can predict many things (avoids after-the-fact story-telling and fact-fitting)
  - It is not ‘ad hoc’ (“for this purpose only”)
- Generality goes with simplicity:
  - Postulates few basic principles or entities
  - Occam’s Razor: Do not postulate the existence of extra laws or entities if they are not needed.

Precision

- Theories should be precise:
  - If a theory is not precise, then possibly no predictions can be made.
  - If a theory is not precise, then maybe only vague predictions can be made, such that the outcome of any experiment can always be seen to be compatible with the prediction.
- In other words, precision helps us put theories to the test.

Conservatism

- New theories should be compatible with existing well-established theories.
- Being conservative makes sense:
  - Evidence that is found in favor of a well-established theory that a new theory conflicts with is likely to be evidence against that new theory.
  - Conservatism avoids postulating new entities and principles, and thus it favors simplicity.

Errors in Science: The Human Factor

And How Science

Has Evolved

to Correct For This

Science is Fallible

- 1. Science is conducted by humans
- 2. Humans are fallible
- 3. Therefore, science is fallible

- Note: the fact that science cannot prove theories with 100% certainty is *not* part of its fallibility: that merely shows the inherent *limitations* of any method that tries to gain knowledge. Even the Perfect Rationalizer would not be able to decide between two competing theories, if both fit the available data equally well.

What can go wrong?

- Mechanical Errors
- Physiological Errors
- Psychological Errors
  - Reasoning Errors
  - Perceptual Errors
  - Interpretational Errors
  - Theoretical Immunity Errors
  - Other Psychological Errors
- Sociological Errors

Mechanical Errors

- Anything that goes wrong in the mechanical execution of the scientific method.
  - Miscalculation
  - Misreading
  - Misrecording
  - Error in experiment (dirty beaker, wrong voltage, etc.)
- These errors are rather innocent. *Repetition* of experiment will usually correct for these kinds of errors. Better technical equipment helps too.

Physiological Errors

- Errors due to physiological factors:
  - Tired
  - Distracted
  - Drugged
  - Sick
  - Etc.
- Science can try and correct for these errors by:
  - Repetition
  - Mechanization

Reasoning Errors I

- Hasty Generalization
  - Relying on too little data
  - Relying on biased data
- Scientists try to correct for this:
  - Gather as much data as possible
  - Gather data under controlled settings
  - Do not accept anecdotal evidence and evidence from personal experience

Reasoning Errors II

- Errors in causal reasoning:
  - Confusing correlations with causations: A correlation between A and B can mean any of the following:
    - A causes B (what we want to conclude)
    - B causes A (*reverse causation*)
    - C causes A and B (*common cause*)
    - Nothing at all (it was just *coincidence*)
  - Post Hoc reasoning (‘after that, hence because of that’)
  - Bad sense of probabilities
- To correct for this, scientists use statistical methods and controlled experiments. Also, causal claims will be made with much caution.

Perceptual Errors

- Our perceptual apparatus is *not* like a camera:
  - Selective Perception (Selective Attention): We notice certain things, but don't notice others
  - Constructive Perception: Our brain fills in missing details and sometimes changes details to make the perception fit our expectations
- Memory is selective and constructive as well!
- To correct for this, scientists use mechanical instruments to measure and record
  - Obviously, this is also because sometimes the human brain is simply too limited to make the necessary observation or to remember all the data

Interpretational Errors

- Science is not conducted in a vacuum. We are doing it with certain preconceptions in place that effect our interpretations, and even our observations:
  - Setting of the sun
  - Slide in biology class
  - Sensitivity of equipment determines what is observed
- This is very hard to correct for:
  - Have other scientists scrutinize work
  - Always keep an open mind and try and come up with alternative theories and views

Theoretical Immunity Errors

- All humans are reluctant to be self-critical
- Scientists are humans
- Therefore, scientists are reluctant to be critical of their own views and theories.

- Through rationalization, self-deception, confirmation bias, and other means, scientists can hang on to ‘their’ pet theory.
- Combined with the fact that we have basic conceptual limitations, theories often change through *paradigm shifts*: conceptual *revolutions*

Other Sources of Psychological Errors

- Herd Instinct
- Wishful Thinking
- Striving for Certainty
- Striving for Simplicity

Sociological Errors

- There are many outside, sociological forces acting on scientists as well:
  - With a new theory can come fame and fortune
  - Scientists need to produce to remain at position
- These forces can effect the reliability of the science in all of the aforementioned ways:
  - Trying to find something, and actually ‘finding’ it, without it being there.

The Evolution of Science

- A final myth about science: science and the scientific method have been the same for several hundreds, if not a couple of thousand, years.
- In fact, it is exactly by becoming aware of the preceding pitfalls of doing science (especially cognitive biases) that science has evolved:
  - white labcoats, notebooks, dedicated and calibrated equipment, peer review, standard operating procedures, repetition, statistical analysis, blind and double-blind controlled experiments: these are all things that only gradually have become part of science as we know it.