SCIENTIFIC METHOD(S)

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"If you want to find out anything from the theoretical physicists about the methods they use, I advise you to stick closely to one principle: don't listen to their words, fix your attention on their deeds. To him who is a discoverer in this field the products of his imagination appear so necessary and natural that he regards them, and would like to have them regarded by others, not as creations of thought but as given realities." (A. Einstein, "On the Methods of Theoretical Physics")

In this lecture, we'll be talking about **scientific method**—that is, the process by which scientists accept or reject scientific theories. While this is often presented to students (especially in K-12 schools) as a straightforward process of formulating and testing hypotheses, the nature of the scientific method has itself been a matter of fierce debate among scientists, historians, and philosophers of science. Ideas about method have changed over time, and lively debates (with real consequences!) continue to this day. To make things even tougher, the methods that scientists *say* that they are following often don't match what is actually being done. The major questions we'll be answering in this lesson include:

1. What does it mean for the scientific community to *accept* a theory, as opposed to merely *use* it, or *pursue* it?
2. What is the difference between the *context of discovery* and the *context of justification?* And what does this have to do with the scientific method?
3. What are some historically important ideas about the scientific method?
4. What are current debates about the scientific method?

This class is the second in a series of planned five classes (however, each class should be independent of the others). Last time, we talked about the nature of scientific knowledge. Next time, we'll talk about if/how science can make progress.

BASIC IDEAS: THEORIES AND MOSASICS

Before diving into our exploration of the scientific method, it will help to begin with a few definitions clarifying how key terms are going to be used (some of which we talked about last time):

A **scientific theory** is just a set of statements (or claims, or propositions) about the way the world is. Well-known scientific theories include Newton's theory of gravitation, Einstein's theory of General Relativity, the theory of evolution via natural selection, and so on. Importantly, saying something is a "scientific theory" does NOT mean "it is just a theory" (in the sense of being uncertain about whether it is true or false). Scientists can have various attitudes about theories:

- A scientific theory is **accepted** if the scientific community of the day believes it is the *best available description of reality that is available to them.* They don't necessarily need to think its perfect (after all, much of their time is spent improving and expanding it). However, it is closer to describing reality than anything other theory on offer. Some currently accepted theories include the "germ theory of disease" (in medicine), the theory of evolution via natural selection (in biology), the "Big Bang" theory in cosmology, and the "standard model" in particle physics.
- A scientific theory is **used** if the scientific community believes it is still useful for some practical purposes, *regardless of whether it is accepted as an accurate description of reality.* In physics, the usual example is Newtonian mechanics (which we KNOW is false, but which is really, really useful in many areas of engineering). This category might also include many theories in psychology, economics, etc.
- A scientific theory is **pursued** just in the case the scientific community thinks it is worthy of further elaboration, *even if it isn't accepted or even useful (in its current form).* There are LOTS of examples of theories that fall into this camp, including well-known ideas such as "String Theory" (in physics) or ideas about "alternative medicine."

At certain points during the history of science, a single theory has dominated others within its in discipline, in the sense that was the only accepted theory, the only used theory, and the only pursued theory (e.g., this was the case with Aristotle's ideas for roughly a thousand years, and Newton's theory for maybe 200 years). However, it is also pretty common to have cases where these three categories diverge—i.e., the community of scientists "accepts" the picture of reality provided by a certain theory, but continues to use theories that contradict this picture (because they are useful in certain contexts) and pursue possible alternatives to it.

The **scientific mosaic** is just the set of theories that are accepted at a given time by the scientific community (such as textbook authors and faculty at big universities). 600 years ago these theories were mostly based on the work of Aristotle (e.g., Earth-centered astronomy, the humoral theory of medicine, Aristotelian logic, and even theology). Around 300 years ago, the mosaic had changed to include Newtonian mechanics and calculus (though it still including humoral medicine and "natural theology"). The contemporary mosaic includes, among many other things, Einstein's theory of General Relativity, Quantum mechanics, Darwin's theory of evolution by natural selection, and so on.

Question: Can you give examples of theories that are (1) accepted by the scientific community, (2) used but not accepted, (3) pursued, even though they aren't currently useful/accepted?

WHAT IS THE SCIENTIFIC METHOD?

For the purposes of this class, we'll define the **scientific method** is a *rule* for theory acceptance or non-acceptance. That is, we apply the scientific method to tell us whether we should move a particular theory into the "accepted" category. While this seems simple enough, it is easy to confuse this with other, related notions:

- Simple examples of scientific methods would be "Accept whichever theory is the simplest," or "Accept whichever theory makes the most successful predictions and fewest failed predictions," "Accept any theory where $p > .05$" or even "Accept whichever theory is most popular with funding agencies". (These last two are especially bad ideas, but are unfortunately part of real science.)
- The scientific method does NOT tell us anything about good "research methods" or about the process of "thinking like a scientist." In fact, according to most statements of the scientific method, it is *completely irrelevant* how you came up with your theory (you had a dream! You found it in an old book! Aliens told you!). The scientific method just takes your end result and tells you whether it should be accepted or not.
- The scientific method that is (actually) accepted by the scientific community of a time often doesn't match up with scientist's (or philosopher's) explicit statements of their **methodologies.** So, for example, scientist-philosophers like Galileo, Descartes, Newton, Darwin, Einstein all had their own ideas of what *should* be the criteria for theory acceptance/rejection. However, looking back, it seems pretty clear that these statements of methodology did NOT always accurately capture the process by which their own theories were accepted or rejected by their peers in the scientific community.

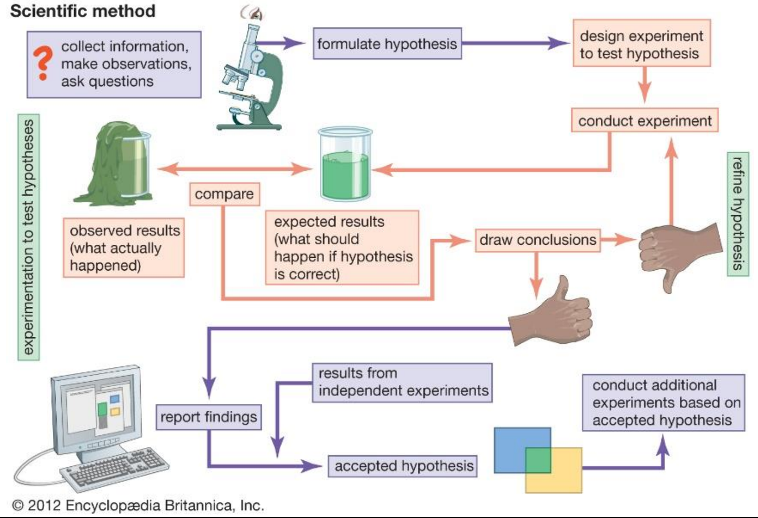
When we ask questions like "What is the scientific method?" we are thus asking questions that belong to what the philosopher of science Hans Reichenbach called the **context of justification** (What makes scientists *justified* in accepting one scientific theory? What role does empirical evidence play? Other factors?) rather than what he called the **context of discovery** (How was a theory discovered? What techniques were used? Where did the idea come from?)**.**

One way of thinking about our question for today is as follows: **Is there any *unchanging* scientific method that determines how the scientific mosaic changes over time?** If there is, then the *reason* we see different theories enter/leave the mosaic might simply be because we have better evidence than we used to (for example, we've just done more experiments!). However, if the scientific method *itself* changes with the mosaic, this might be more worrisome, since it would suggest that, along with changes in scientific theories over time, there are ALSO changes in the criteria by which these theories are accepted or rejected.

Question: Try to come up with your OWN definition of the scientific method. Now, double-check to see whether it meets the requirements above—that is, does your definition explicitly say when theories should be accepted?

WHAT'S WRONG WITH THE "NAIVE" PICTURE OF THE SCIENTIFIC METHOD?

In introductory science textbooks (at both the high-school and college-level), students are taught the following picture of the scientific method, which is often attributed to Francis Bacon or his contemporaries in 17th century Britain. While there are valuable things about this picture, it also leaves out quite a bit.

<table>
<tr><th>The Naïve Picture</th><th>Three Problems With The Naïve Picture</th></tr>
<tr><td>
</td><td>1. This isn't a method at all, in the sense we've defined! It doesn't actually tell us anything about when the evidence we've collected is good enough for us to accept a theory (or conversely, when the evidence is sufficient to reject it).
2. This failure to discuss acceptance can be a problem if students come to (falsely) believe that the scientific method will lead unerringly to true theories. This isn't true (ask any scientist!). When these students discover this later in life (e.g., from climate science skeptics or anti-vaccination campaigners) it sometimes can lead them to reject science altogether.
3. This picture also conflates two different issues:(a) the processes by which individual scientists or research groups generate and test hypotheses (here, the worry is that this picture is far too simple) and (b) how the scientific community as a whole decides to accept/reject hypotheses.</td></tr>
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At best, this is a partial picture of how experiments might contribute to the acceptance or rejection of a hypothesis (but which doesn't actually talk about criteria for acceptance or rejection!). While a full discussion of the issues with the "naïve" picture of the scientific method are beyond the scope of this talk, it's an important example of the connection between philosophy, history, and science. The *reason* that this is taught to students seems to have more to do with textbook authors' (often unexamined) beliefs about the history and philosophy of science than with any study of what scientists (either now or historically) actually do.

Question: Is there a better way of teaching students "how to do science" (besides having them memorize the picture above)?

ARISTOTLE'S METHODS: UP TO PRINCIPLES AND BACK DOWN AGAIN

"If, then, understanding is as we posited, it is necessary for demonstrative understanding in particular to depend on things which are true and primitive and immediate and more familiar than and prior to and explanatory of the conclusion." (Aristotle, Posterior Analytics, 70b)

Many books on the history of science begin with the so-called "Presocratic thinkers" (such as Heraclitus, Zeno, Parmenides, and Democritus) of the Ancient Greek world, who lived in what is now the west coast of Turkey. These thinkers were distinguished by the fact that they offered somewhat **naturalistic** accounts of why the world was the way that it was, as opposed to mythical-religious accounts. Some of these ideas (such as Democritus's idea that the world was composed of nothing but tiny "atoms" in the "void") would, thousands of year later, serve as important precursors for theories proposed during the "Scientific Revolution." However, so far as we can tell (and given how little is left of their writings, this often isn't very much!), these thinkers didn't have much in terms of scientific method—they simply proposed whatever theory seemed best to them. **Plato** was considerably more systematic (and his account of how knowledge works has a lot to say about "formal" sciences like math or geometry), but he was highly skeptical than anything could be learned through observation of the physical world (which rules out most of contemporary science!).

By contrast, Plato's student **Aristotle (385-322 BCE)** offered a much more fleshed-out picture of how investigation of the natural world (or what we would now call "science") should proceed, and under what conditions we should accept a scientific theory. He thus describes something like a "scientific method." Many of his ideas about how science would work would be widely adopted by later Roman, Christian, and Muslim thinkers. As we'll see later, there are important differences between Aristotle's method and more modern ideas, which will cause problems for the idea there is only "one" scientific method.

GENERAL PRINCIPLES. These general laws (such "all mammals give live birth" or "all physical objects move toward the center of the earth" or "humans are rational animals") describe the essences of the things in our world.

Experts make INFERENCES from particular -> general based on observation (inductive reasoning)

We use these principles to EXPLAIN our world (deductive reasoning).

OBSERVATION of particulars, particularly by experts. For example, observations of individual mammals, humans, or physical objects.

EXPLANATION of particulars. For example, we can now use what we know about the essences of mammals, physical objects, or humans to explain other things about them.

So when do we accept a theory? Aristotle, like most contemporary scientists and philosophers of science, accepts that there is a distinction between the "particular" things of the world and the general laws/principles. Moreover, as we can see in the diagram above, he ALSO agreed that the way we gain knowledge of general principles depends, at least in part, on our observations of the particulars (a big difference with his teacher Plato!). However, unlike most modern scientists, he suggests that our knowledge of principles will, in the end, be secured in large part by **"dialectic"** among the relevant experts. So, for example, let's consider the case above, where we are trying to figure out the "essence" of mammals, or physical objects, or humans. What do we do?

1. We make lots of observations of particular mammals, physical objects, and humans. We'll never directly *see* the principles, however, and some of things we do see (humans behaving irrationally, rocks flying through the air) won't quite our model.
2. These observations will lead to debates among subject-area experts (unlike Plato, Aristotle does NOT think that academic philosophers have all the answers!). They'll try to figure which properties are *essential* to humans, physical objects, and mammals, and which properties are merely accidental.
   a. These debates will include not only observations, but (importantly) theoretical considerations about what seems "natural" or "best." Unlike modern science (especially starting in the 20^{th} century), Aristotle does NOT allow for the fact that a theory might be counterintuitive but still be correct.
   b. For example, humans are the only animals that talks, and the "purpose" of language is express rational argument, so rationality must be the essence of humanity. (This is an over simplification, but you get the idea).
3. At some point (hopefully) the community of experts will reach a consensus. Then, we should accept the theory!

Aristotle provides a model of this process in his own work, where he spends a lot of time discussing the history of previous "scientific" theories (such as those provided by the pre-Socratic thinkers) and noting places where they (1) fail to accord with experience or (2) make claims that he has conceptual objections to (this is why he rejects atomism). He inevitably offers his own theories of physics, biology, political science, etc. as a sort of "middle ground" that incorporates the best of each historical theory. Aristotle only rarely suggests that we might need more observations to determine whether a theory should be accepted (though it should be noted that Aristotle and his students did more empirical research than many later "Aristotelians"). Why this may seem strange to us moderns, it's not clear why (on Aristotle's method) more observations would make for better science. After all, without the notion of an **experiment** (a crucial part of modern science), there's little reason to think that future observations will differ qualitatively from anything we've observed so far.

Aristotle's picture of the scientific method (basically, taking everyday observations of the world and then having "experts" argue about their import) was highly influential. On the Aristotelian picture, there was no clear distinction between the methods of the "formal" sciences (math, logic), "natural" sciences (biology and physics), and things we wouldn't consider science at all (philosophy, theology, etc.). In every case, the "method" was simply to look around for "first principles" which captured the "essential nature" of whatever was being studied. Many of the thinkers involved in the "Scientific Revolution" (which started around 1600)—including Francis Bacon and Rene Descartes—saw themselves as reacting against Aristotelian methods (and NOT just Aristotelian conclusions). However, as we'll see, it took quite a while for the scientific community to move away from this method.

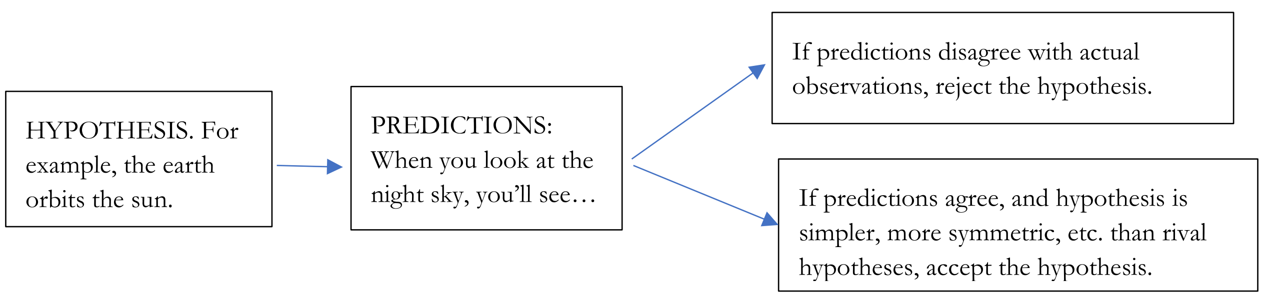
COPERNICUS AND THE METHOD OF HYPOTHESIS

One of the first descriptions of something that sounds like the "modern" scientific method comes from **Nikolas Copernicus (1473-1543),** in his discussion of how he came to his theory about a sun-centered universe:

For a long time, then, I reflected on this confusion in the astronomical traditions concerning the derivation of the motions of the universe's spheres. I began to be annoyed that the movements of the world machine, created for our sake by the best and most systematic Artisan of all, were not understood with greater certainty by the philosophers, who otherwise examined so precisely the most insignificant trifles of this world. For this reason I undertook the task of rereading the works of all the philosophers which I could obtain to learn whether anyone had ever proposed other motions of the universe's spheres than those expounded by the teachers of astronomy in the schools. And in fact first I found in Cicero that Hicetas supposed the earth to move…Therefore, having obtained the opportunity from these sources, I too began to consider the mobility of the earth.

Having thus assumed the motions which I ascribe to the earth later on in the volume, by long and intense study I finally found that if the motions of the other planets are correlated with the orbiting of the earth, and are computed for the revolution of each planet, not only do their phenomena follow therefrom but also the order and size of all the planets and spheres, and heaven itself is so linked together that in no portion of it can anything be shifted without disrupting the remaining parts and the universe as a whole…(De Revolutionibus Orbium Coelestium*)*

While Copernicus sounds a bit like an Aristotelian early on (with all of his talk of what previous authorities/experts had said), he quickly proposes a very different method for determining which theory should be accepted, which has to with *how well his hypothesis could explain the observed phenomenon*. This method looks much more modern:



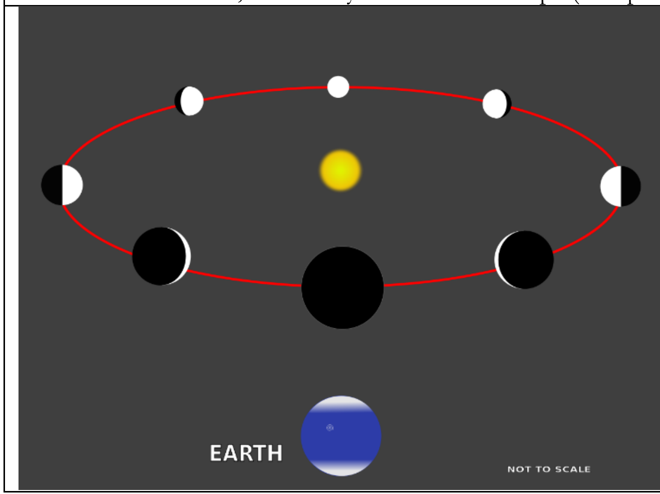
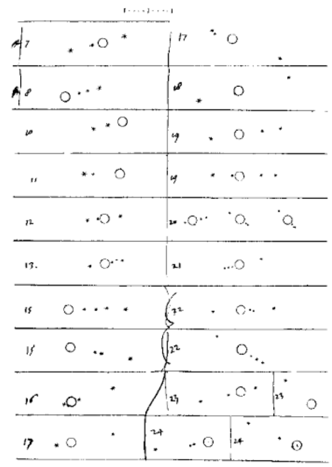
To modern eyes, this looks right! However, it took a *long* time after Copernicus died for astronomers to accept his theory? Two reasons: (1) Copernicus's own argument doesn't quite do enough, in terms of the modern scientific method and (2) the astronomers of the day didn't actually accept the modern scientific method!

The Importance of Making "Novel Predictions." Copernicus argued that his theory could do just as well as the rival, earth-centered view (the **Ptolemaic model** of the solar system) in terms of making accurate predictions AND that it was simpler and more harmonious. (After all, his theory didn't have the planets moving all over the place in crazy *epicycles)*. However, he didn't change many minds with his view—as it turns out, the vast majority of scholars of the day weren't willing to abandon their views about the **ontology** of the universe (i.e., their views about the way existence worked at a fundamental level) *merely* because Copernicus's model was a bit less messy than the Ptolemaic view they currently adopted. This is unsurprising! As a rule of thumb, modern scientific method tends to accept changes to accepted ontology only when the rival theory has made **novel predictions—**that is, it has made predictions that *disagree* with the current theory, and which are shown to be correct. It would be one thing if Copernicus was simply tinkering with the existing model (*that* sort of thing doesn't require novel predictions). However, proposing a major change to the accepted worldview requires really good evidence!

GALILEO'S FAILURE AND DESCARTES' SUCCESS

"Some years ago I was struck by the large number of falsehoods that I had accepted as true in my childhood, and by the highly doubtful nature of the whole edifice that I had subsequently based on them. I realized that it was necessary, once in the course of my life, to demolish everything completely and start again right from the foundations if I wanted to establish anything at all in the sciences that was stable and likely to last." (Descartes, Meditations on First Philosophy)

Galileo Fails to Convince. This brings us to someone who DID provide novel predictions in support of Copernicus's model of the solar system**—Galileo Galilei (1564-1642)**. He used Copernicus's theory (along with his telescope) to observe, among other things, the phases of Venus and moons orbiting Jupiter. This was a big deal, as these didn't fit AT ALL with the view that everything orbited around the earth. Conversely, this DID fit with Copernicus's model of a sun-centered universe. However, unlike Copernicus, Galileo didn't provide any sort of Aristotle-friendly argument about why/how this fit into the larger picture. In other words, he didn't say anything about the essences of bodies, their natural movements, the authority of other scholars, etc. Perversely, this failure to observe the "rules of the game" ended up getting Galileo into much bigger trouble than Copernicus ever had.

The Phases of Venus, as Seen by Galileo's Telescope (Wikipedia)	Galileo's Sketch of Jupiter's Moons
	

Descartes as the Bridge Between Worlds. In contrast to Galileo (who spent the last years of his life confined to his house as a punishment for publishing heretical science), **Rene Descartes (1596-1650)** managed not only to convince many of his contemporaries to endorse the idea of a sun-centered universe, but ALSO to abandon the underlying Aristotelian ideas about physics that had inspired this motion (e.g., the four elements and their motions). Notably, however, he did NOT rely on anything like the modern scientific method to do so (he wasn't a great experimentalist, and didn't offer any novel predictions). Instead, he offered an argument that satisfied the demands of the Aristotelian method adopted by the scientific community of his day. He began by adopting a stance of **methodological doubt** (i.e., he began by assuming that any statement that *could be false was false.*). On this basis, he argued that *essence* of material objects was simply the fact that they "took up space", and that their motions were governed by algebraic **laws of nature** (his **Cartesian coordinate system** made it considerably easier to describe such laws). He offered the first law of **inertia** (which Newton would later show to be incorrect). Finally, he offered a technical workaround to assure the clergy that the earth wasn't "really" moving by claiming that ALL motion is relative in some sense (it was just that the model that described motion from the point of view of stationary sun was a lot theoretically neater than the one that assumed a stationary earth).

OK, So What's the Point of All This? While Descartes' success was crucial to the rise of "modern" science, it also shows us something surprising about the scientific method: namely, that he did NOT argue for his theory on the basis of the modern scientific method, but instead argued for it using a different (Aristotelian) method. The contrast to Galileo (who tried, and failed, to convince his colleagues using something closer to the modern method) is especially important. This suggests that the "scientific method" *itself* changes over time, just as do the theories we use it to evaluation.

Question: Galileo and Descartes are both important (but very different!) figures in the history of science. Which one do you think is closer to "modern" science? Why?

CONTEMPORARY DEBATES

While scientists have a wide variety of explicit methodologies—that is, their *descriptions* of the reasons for which they accept or reject theories vary quite a bit—the scientific community as a whole seems to have adopted something like Copernicus's method of hypothesis, but with an emphasis on the importance of novel predictions. This can (roughly) be described as follows:

> A theory that proposes a new ontology should be accepted based on the extent to which it can (1) it can successfully account for the predictions of the old theory, (2) it generates novel predictions, which agree with observations and (3) it has other theoretical virtues (such as simplicity, or research potential).
>
> By contrast, a theory that merely improves on the existing ontology can be accepted if (1) improves on the accuracy of the existing theory and/or (2) doesn't improve on the accuracy, but has other theoretical virtues. Novel predictions are not needed.

This, of course, isn't a complete picture of how theory acceptance/rejection works, and many contemporary philosophers of science doubt that we can ever provide such a picture (mostly because different scientific disciplines work somewhat differently). Nevertheless, its worth closing by considering a number of the most popular ideas/claims about the scientific method currently popular among both scientists and philosophers of science. These ideas are all compatible with the general method just discussed, but each build on it in different ways.

Karl Popper's Falsification. The Austrian philosopher Karl Popper argued that a theory is *scientific* to the degree that it made *falsifiable* predictions. That is, a theory should make predictions who accuracy we can check, and which we might discover to be wrong. Popper argued that, while we could discover whether a given scientific theory was true, we COULD discover whether it was false. The scientific method, in its most basic form, consists of strenuous attempts to falsify our theories, and conditionally accepting those theories that have survived the most "strenuous" attempts at falsification.

Bayesianism. Unlike Popperians, Bayesians (as advocated by philosophers like Rudolph Carnap) think that we CAN and SHOULD talk about the truth of scientific theories—we should just do so probabilistically (i.e., we should base theory acceptance on *how likely* we think it is that this theory is true/accurate, given our evidence). While we should never expect to have 100% certainty that a given theory is true, the mathematical laws of probability assure that we can be *more confident* in a theory that makes surprising/novel predictions. So, if a theory T predicts that event E will happen AND we think it is really unlikely that E will happen (were T to be false), the occurrence of E is really good evidence in favor of T. Theory acceptance is just a matter of comparing probabilities (e.g., "We'll accept whichever theory has the highest probability of being true.")

Feyerabend's Methodological Pluralism. Finally, there is the (in)famous philosopher of science Paul Feyerabend, who argued that there is no scientific method, and that K-12 science classrooms, grant agencies, journal referees, university hiring committees, etc., should stop pretending that there is. (At one point, he suggests funding/teaching about extra sensory perception, though it is tough to tell how serious he is). In his more moderate moods, Feyerabend seems to be proposing a sort of **methodological pluralism,** where scientific methods should be thought of the same way that scientific theories are. So, for Feyerabend, it is not that there's anything wrong with Aristotle's method, or Copernicus's, or Popper's, or Bayesianism. He just thinks that we should approach debates about "scientific method" the same way we approach debates within science. We should "teach the controversy," and stop trying to police the borders of science (e.g., by trying to find criteria that "prove" that creationists aren't really doing science). Feyerabend's argument for this seems to be an evolutionary one: the only way to discover the "best" methods is to cultivate a whole bunch of different methods, and let them battle it out.

To the extent that practicing scientists are aware of these debates, many/most identify as Popperians or Bayesians, especially in the "hard" sciences. By contrast, Feyerabend's ideas about methodological pluralism are far more influential in areas such as sociology, educational research, and related areas.

Different ideas about method can, in some cases, have very real consequences for practice. So, for example, the **replication crisis** currently occurring in social psychology and other areas of science (basically, attempts to replicate many/most "foundational" studies in the field have failed, even though these studies are taught in textbooks, used to plan government interventions, etc.) depend, at least in part, on failures to think carefully about questions of scientific method.

*Question: What might some of the *practical* consequences of disagreements about scientific method? How might people with different methods "do science differently"? Would they disagree about which theories to accept? Which sorts of experiments to conduct?*