HOW DOES SCIENCE CHANGE OVER TIME?

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In today's lesson, we'll be thinking about the process of scientific change, and the ways in which the scientific community comes to accept new theories and methods over time. Along the way, we'll be answering the following questions:

1. What is a *scientific mosaic?* How has the scientific mosaic, in fact, changed over time?
2. What is the process by which science changes? Is this a *rational* process?
3. How have historians and philosophers of science answered this question? Why do they disagree?
4. Can there be a general theory of scientific change? What sorts of problems would this theory need to solve?

In order to answer these questions, we'll be introducing a variety of ideas from the history and philosophy of science. This is the third in a series of five planned classes on the history and philosophy of science. However, don't worry if you've missed the first two lectures! We'll start by reviewing all the necessary concepts before moving on to our questions for today.

THEORIES, METHODS, AND MOSAICS: THE BASIC IDEAS

Before starting our investigation of scientific change, it will be helpful to introduce (and/or review) some terminology. Following Hakob Barseghyan (2015), among others, we'll be using the following terms:

- A **scientific theory** is just a set of claims (or "propositions") about the world. Theories can be true or false, and scientists have different attitudes about different theories. We'll say that a theory is **accepted** just in the case that the scientific community agrees that it is *the best available description of reality currently available.* By contrast, a theory is **used** just in the case that there are still some practical uses for it, and it is **pursued** if scientists are pursuing research on it. It's important to note that theories that are NOT accepted might still be judged useful (e.g., Newtonian mechanics helps us build bridges). Similarly, scientists often pursue theories (such as "String theory") that the scientific community doesn't accept.
- Scientific theories come in two general types: the **formal theories** of mathematics (and some areas of computer science, statistics, etc.) that can be *proven* to be true or false, and the **empirical theories** of biology, physics, economics, etc. Since empirical theories, by their nature, involve **synthetic** claims about the world that might (conceivably) turn out to be false. For this reason, we can never have "absolute" or "infallible" knowledge that a given empirical theory is actually true. (However, this doesn't prevent us from making comparative judgments about which theories are *more likely* to be true—this is a big part of empirical science!).
- A scientific **mosaic** (or "scientific worldview") is just the set of all scientific theories *accepted* (not just used or pursued!) by the scientific experts of the day, such as university faculty, researchers, industry scientists, textbook authors, etc. The scientific mosaic has changed over time, and continues to change!
- A scientific **method** is a rule (usually implicit) for deciding whether a new theory ought to be incorporated into the mosaic. This includes criterion about theory acceptance, as well as the demarcation between science and non-science ("Is the subject matter of this theory really *science?*") and also the *compatibility* between different theories ("If we take this new theory into the mosaic, are we going to have tp abandon any of our current theories?").

Some major changes in the scientific mosaic. In previous classes, we talked a fair amount about the ways in which the scientific mosaic has changed over time. In particular, we thought about the sorts of scientific theories that would have been accepted at a single elite institution (such as Oxford University in England) have changed from 1420 CE to 1720 CE to the 2020 CE.

- The scientific mosaic of 1420 was dominated by **Aristotelian** ideas about physics, biology, medicine, logic, and social science. According to Aristotle, everything sort of "thing" studied by science (from the "four elements" to animals to human beings to God) had an "essence" or purpose, which science aimed to discover. The essences ranged from the simple (the essence of fire involves moving "up", while that of the planets involves moving "circularly") to the complex (it is the essence of humans to be "rational animals"). The scientists of the day did NOT demarcate between science and religion, and so Thomist theology (itself built on the work of Aristotle) would also count as scientific. The mosaic also had formal sciences (Euclidean geometry, categorical logic) which are still with us.
- In England, the scientific mosaic of 1720 was adapting to **Newtonian** theories about physics. Leading scientists had almost universally adopted Copernicus's ideas about the helio-centric solar system, and were in the process of adopting the formal theory of calculus. Euclidean geometry and categorical logic still had no rivals, and many things that are today considered "unscientific" (theology, alchemy, etc.) were firmly in the mosaic. Aristotelian ideas remained dominant in medicine and biology.

- By 2020, the scientific mosaic included *many* theories covering a *huge* number of different domains (far more than in 1720 or 1420). In physics, the foundational theories remain General Relativity and Quantum mechanics, while biology is based on the "Modern Synthesis" of Darwin's evolutionary theory and Mendelian genetics. Formal theories such as those dealing with geometry (starting in the 19th century) and logic (starting in the 20th century) have expanded significantly, in tandem with results in physics and computer science, among other things.

Question: OK, so this is a lot of material to cover very quickly. The most important distinction for the rest of this lecture will be the distinction between "theories" and "methods" and between "formal" and "empirical" theories. How would you describe these concepts in your own words? Can you think of any examples?

SCIENTIFIC METHODS CHANGE, TOO

Scientific methods change, too. Not only do scientific theories change, so do the methods used to evaluate theories for inclusion in the scientific mosaic. For example, the Aristotelian "method" placed a high emphasis on what subject-matter experts believed about the *essence* of their subject, while more modern methods emphasize the importance of controlled experiments. In particular, most branches of modern science accept something like the **hypothetico-deductive method,** according to which theories proposing new entities or forces should be accepted only if they generate *novel predictions* (i.e., made successful predictions of events we otherwise wouldn't have expected).

An example of how methods change: "Should we accept drug X as the best treatment for condition C?" This is an example of a question that has come up a lot in the history of medicine, for good reason—patients (and their physicians) want to make sure they get effective treatment for their condition. It is also a specific type of a general question about scientific theories: "Should theory T be accepted?" Here are some simplified descriptions of real methods that have been adopted over the last 1,000 years or so, together with some of the problems that (eventually) led the scientific community to adopt new methods.

METHOD	***PROBLEM***
Aristotelianism. Drug X should be accepted as the best treatment for condition C just in the case that it seems to experienced, expert observers (in this case, physicians) to work well. In other words: we should trust that individual physicians know what they are doing, since (1) they have lots of experience with disease, and (2) their training enables them to draw on lots of other experience.	This method might be better than "accept whatever theory strikes your fancy," but not by much. It turns out that physicians' personal experience doesn't allow them to "see" the causal efficacy of treatments in the way Aristotelians might have hoped. The problem is that there is just too much "noise"—physicians, like other humans, are too quick to conclude that patients who get better did so *because* the treatment worked, as opposed to luck.
Simple Induction. Drug X should be accepted as the best treatment for condition C just in the case that people who take drug X recover at a higher rate than those taking other drugs.	This is a definite advance, as it attempts to avoid the pitfalls of relying on the psychology of individual physicians. However, unfortunately, mere "correlation" doesn't guarantee "causation." For example, when cigarettes were first introduced, it is likely that the average cigarette smoker was healthier than the average user of other tobacco. (Why? Just because they were likely younger!).
Controlled experiments. To avoid the pitfalls of simple induction, we can test a drug's efficacy by dividing subjects into two groups: "control" (who don't get the drug) and "experimental" (who do get the drug), and compare how well they do. We adopt drug X only if the experimental group does better than the control group.	There may still be a lot of differences between the control and experimental group that can make it difficult to detect the actual effect of the drug. For example, people who *choose* to take the drug might be healthier (or less healthy) than those that don't; their health might be affected by their *knowing* they got the drug; and they might even be affected by the researchers knowing whether they got the drug (e.g., perhaps the researchers treat the people getting the drug differently).
Controlled experiments: Placebo, Randomized, Double-blind. Over the last 100 years, controlled experiments have been improved in a number of ways. In many cases, we assign subjects to control/experimental groups *randomly,* and *blind* both the researchers and the subjects to whether they are getting the treatment. To assist in this blinding, we often give *placebos* (such as sugar pills) to the control group.	While the double-blind, placebo-controlled **randomized control trial (RCT)** is sometimes called the "gold standard" in medicine, problems remain. First, there are many cases in which we can't do it (e.g., "placebo" surgery can be difficult), or shouldn't do it (e.g., we shouldn't force people to smoke cigarettes to determine if they cause cancer!). In recent years, there has also been a widespread recognition that many research times selectively report the *statistics* from these experiments and that journals selectively *publish* reports of experiments. This has contributed to the *replication crisis,* in which researchers have found themselves unable to "replicate" the results of many previous RCTs. This, in turn, has led to concerns about the efficacy of treatments that were based on the results of these RCTs.
Recent changes. Medical science (like science in general) has continued to adopt new methods. Recent ideas include *preregistration* of experiments (i.e., submitting experimental methods to journals *before* the results are known), greater commitment to publishing *replications* and *negative results,* and more stringent requirements for statistical measures.	

So what's the take-away? Scientific change doesn't just involve a change in theories, it also involves changes in the methods by which we decide to accept or reject these theories. So, over the history of medicine, we scientists have regularly changed their theories about "the best drug/treatment for condition C". However, they have ALSO changed the methods by which they determine what the "best" treatment is.

Question: In recent years, there has been increasing levels of distrust in medical science (e.g., people refusing to get vaccines, or to follow public health guidelines). Why is this, and how might it relate to questions about scientific method? For example, how much do you think non-specialists (most of us!) actually know about how drug testing works? Will changes/improvements to methods lead to greater trust in medical science? Why or why not?

ARE THERE ARE GENERAL PRINCIPLES OF SCIENTIFIC CHANGE?

If what we've said so far is correct, then the scientific mosaic regularly changes in at least two ways: the *theories* it includes change, and the *methods* used to evaluate these theories change. We're now in a place to ask some questions that have long interested philosophers and historians of science (as well as many scientists!):

1. Are there are any "general principles" describing how science (both methods and theories) changes over time, regardless of time/place?
2. If there are general principles of scientific change, what are they? If there are not any general principles of scientific change, how should we go about studying science?
3. Is scientific change a *rational* process? A *predictable* process?

In the rest of this lecture, we'll be thinking about questions 1 and 2. In the next class, we'll be thinking more about question 3.

Some Skeptical Arguments Against "General" Principles of Scientific Change. Over the last few decades, many (though certainly not all) historians and philosophers of science have given up hope of finding any general principles of scientific change. Here are a few of their reasons:

1. **"Philosophers (not to mention scientists) have a bad track record when it comes to describing scientific change. Why should we expect them to do better in the future?"** Philosophers and scientists have offered a LOT of ideas about how science should work, including ideas about what the perfect "method" would be, and under what sorts of conditions people should be willing to adopt new theories and abandon old ones. The problem is that, so far, all of these theories have failed to accurately capture how science has *actually* changed. For example, philosopher-scientists such as Aristotle, Descartes, and Newton all thought that empirical science should/would become more and more like formal science, until we were able to *deductively prove* that theories are true. This never happened (all of their "proofs" of their own theories failed), and empirical science has settled for theories that are "more likely" to be true. In the 20th century, many philosophers tried to say more about what "more likely" meant using statistics and probability theory (and the *types and amount* of evidence scientists should require before adopting a new theory). While this led to some genuine advances (and laid the groundwork for current advances in Artificial Intelligence and Machine Learning), there's still no generally accepted account of how this applies to theory acceptance or rejection.
2. **"Too much has changed during the history of science. Any attempt to draw general conclusions about how science works is doomed to fail."** According to this argument, the places and times in which different scientists have worked have changed a lot, as have the methods that these scientists have used. In fact, these changes have been SO significant, that there's really nothing held "in common" between scientists of different eras that we could use to try to "explain" scientific change. So, for example, consider the "scientific communities" of pre-Socratic Greece, that of Tang Dynasty China (around 800 CE), and 18th century Britain. These people spoke different languages, lived in societies with radically different political and religious structures, etc. Moreover, the "scientific methods" and "scientific theories" adopted by these communities reflected these differences. When pushed to its extreme, this argument concludes that it is impossible to formulate principles that are both *interesting* (i.e., that actually tell us something we didn't know!) and *true.*
3. **"Science isn't a special/unique part of human experience. Scientific change should be studied by historians and sociologists, using the same methods they use to study general changes in cultural practices (such as language, etc.)"** According to this approach, the truth/accuracy/usefulness of a scientific theory or method plays no significant role in explaining why the scientific community adopted these theories. Instead, we should seek to explain the adoption/rejection of these theories by considering the social/cultural forces at play during the time. In a famous book called *Against Method,* the philosopher of science Paul Feyerabend goes even further than this, and argue that science in the current age is an all-consuming *ideology,* in much the same way that (some version of) Christianity was an ideology in Medieval Europe, or that (some version of) Marxism was an ideology in Communist dictatorships. He argued that science should be studied with the same tools as these ideologies (and should be viewed with similar levels of suspicion).

Should we accept these skeptical arguments? All of these arguments bring up relevant problems that any "general" account of scientific change will need to address. However, even taken together, they are far from definitive. For example, the first argument ("the bad track record") argument risks concluding too much: for example, it seems we could this form of argument to conclude that philosophers will never solve any problem they haven't solved before! The history of science shows the mistake in this—there are many, many problems which "philosophers" struggled with for hundreds (or even thousands) of years before finally solving them, at which point they gave birth to new sciences (of physics, biology, computer science, etc.).

The second and third arguments can be read in two ways. On the first, "weak" reading, they are simply saying that "science works differently in different times and places, and no general theory of scientific change is ever going to predict how science changes in every culture." This is obviously true, but it is perfectly compatible with there ALSO being some general principles that can describe/predict scientific change. On the other hand, these arguments can be given a "strong" reading, according to which culture/society *completely determines* what scientific theories are accepted (on this view, the actual content of scientific theories turns out to be of secondary import; instead, what matters was how the acceptance/rejection of scientific theories related to the cultural dynamics in a given place and time). This strong view immediately runs into a problem: if science is a "fad" (as it seems to be on this view) how do we explain its success (for example, in helping to build useful technology?).

Question: Many philosophers, historians, and scientists have hoped to show that the process of scientific change (i.e., the adoption of new theories and methods over time) is a *rational* process that can, in principle, be understood by philosophers and historians. However, as we've seen, there are some reasons to be skeptical that this is possible. How much should the outcome of this debate concern us?

FOUR LAWS OF SCIENTIFIC CHANGE?

Hakob Barseghyan (2015, p. 63) has recently proposed that there are four "laws" that describe how science changes over time. He argues that these principles can overcome the skeptical arguments just discussed. While his principles have not been widely adopted, they provide a useful example of what a "general" account of scientific change might look like:

1st Law: Scientific Inertia. *"An element of a mosaic maintains its state in the mosaic unless replaced by some other element."* The basic idea here can be illustrated with an example from medicine. If our "current best practice" is to treat condition C with drug D, then *we will continue to do so until we find some better, alternative treatment (or until we discover that drug D does more harm than good).* Scientists, like most humans, don't change their practices and ideas willy-nilly. So, we can assume that, absent some positive reason to change their attitudes toward some particular scientific theory, they won't. They will accept the theories they currently accept; find useful the theories they currently find useful, and pursue the theories they currently pursue.

2nd law: Theory Acceptance. *"A theory becomes accepted into a mosaic only if satisfies the mosaic's acceptance criteria."* The idea here is that theories are always and inevitably going to be judged by the methods that the scientific community *currently* accepts, and NOT by the method the scientists proposing the new theory think they ought to accept. For example, in a previous class, we discussed the differing fates of Galileo and Descartes, both of whom defined Copernicus's theory of a heliocentric solar system. Galileo argued for this theory based on considerations (such as carefully reported experimental results) that sound very convincing to contemporary scientists. However, his argument was rejected (and he was imprisoned). By contrast, Descartes argued for the theory by respecting, in large part, the "methods" of Aristotelian science *even while arguing for replacing its preferred theories*. He talked a lot about *essences, first principles, natures, etc.* Once the theory was accepted, of course, Galileo was quickly seen as the scientific revolutionary he was.

3rd Law: Method Employment: *"A method becomes employed in a mosaic only when it is deducible from some subset of other elements of the mosaic."* The second law said that theories will be accepted (or not) based on currently accepted methods. The third law says that which METHODS are adopted or used will itself depend on which theories are currently accepted within the scientific mosaic. So, for example, the acceptance of Descartes' theory (itself based on Aristotelian methods!) led scientists of the day to see the world in a very different way: for example, they began to appreciate the importance of mathematical laws, the action of unseen forces described by "laws of nature", etc. This eventually led them to adopt new scientific methods very different from those of Aristotle. Both experimentation and mathematics began to place a much bigger role in which *future* theories they adopted. By contrast, the "intuitions" of experts no longer had as much weight. This change in methods would help pave the way for the acceptance of new theories, such as Newton's, which disagreed with Descartes.

This same sort of process can be seen in the medical example (regarding drug testing) that we began with. The *reason* that scientists have changed their methods for testing drugs is because of changes that have occurred in scientific theories such as statistics and psychology. So, for example, advances in statistics (and computing) gave us better insight into what how we should choose the sample sizes for experiments, how big of "effects" we should expect, and so on, while advances in psychology made us more aware of the way that unconscious bias by experimental subjects (and scientists!) might interfere with experiments (and the need to take account of this).

0th Law: Compatibility: *"Two elements become compatible within a mosaic only when they satisfy the mosaic's compatibility criteria."* In much the same way that scientists will always judge new scientific theories using their current methods (and will accept only theories that these methods deem "good enough"), they will ALSO rely on their current **compatibility criteria** to determine whether a new theory is compatible with existing theories. In the formal sciences (such as mathematics), this is very straightforward: since we should only accept theories that we have *proved* to be true, no two theories within our mosaic should ever contradict one another. So, for example, while we might have different "types" of geometry, these theories are all of the form "IF the following axioms are assumed to hold, then so and so follow."

By contrast, things are much messier in the empirical sciences, such as biology, physics, and chemistry. Here, scientists often accept theories (such as quantum mechanics and general relativity) that DO contradict one another, at least in certain cases (for example, "black holes" can be described using either QM or GR, but these descriptions don't agree!). This reflects the fact that we can never have *certain* knowledge in the empirical sciences, and often have to settle for theories that are "the best we currently have." This is an even bigger issue in social science areas like psychology, economics, or sociology, where the scientific community accepts *many* competing theories. That being said, there are clear limits to this, and we can find clear examples of theories that *would* be deemed "incompatible" with current approaches. (For example, economists would likely reject a theory that entailed "the economy can't be described with math," just as psychologists would reject theories that entailed "your mental states have nothing to do with your brain.").

Question: A good starting point for assessing a proposed philosophical claim (such as the "four laws" above) is to ask two question. First, to what extent is the claim INFORMATIVE? That, if you became convinced that these four laws were true, would this tell you something interesting about the world? Second, is the claim TRUE? So, for example, Barseghyan's arguments for these laws are almost entirely drawn from the history of "Western" science (Aristotle to Descartes to Newton….). How well do these laws describe what happens in other places and times? To different areas of contemporary science?)

(Here, I don't have the answers! This is in an invitation to think about how these might apply—or not—to topics that you know something about.)

WHY DOES SCIENTIFIC CHANGE MATTER?

The discussion so far can be summed as follows:

1. Science changes over time. Scientists come to accept new theories and reject old ones.
2. Scientific methods (the things used to *judge* whether theories are acceptable) also change over time.
3. Philosophers and historians have often wondered: "How does the process of scientific change work? Are there any general laws that we could use to describe it?"
    a. Many have hoped we could show that scientific change was rational, and that is thus reasonable to expect science to make continual progress.
    b. Others ("skeptics") have argued that there are no general laws of scientific change that hold across different times and places. How (and whether) science changes and progresses depends more on cultural/historical factors that anything science itself.
4. One proposed set of "laws of scientific change" can be summarized as follows:
    a. A theory accepted by the scientific community will stay accepted, until it is replaced (inertia).
    b. Theories are accepted or rejected based on the scientific community *current* methods.
    c. Scientific methods change in response to the theories that we accept.
    d. Whether two theories are deemed "compatible" with one another will depend on what sort of theories they are.
5. Not everyone accepts these "laws."

In the next class (if you come back!), we'll be talking about what all of this means for the prospect of **"scientific progress."** That is, all things being equal, can we expect that this process of scientific change will lead us to better, more accurate, more useful descriptions of the world? Or not?

QUESTIONS FOR DISCUSSION

1. What would you say the biggest "change" in science has been in your life? Why and how do you think this change occurred?
2. How do you think science might change over the next 20 years? The next 100?
3. In general, when scientists adopt new theories/methods, how much do you think this driven by "rational" factors (such as responding to new evidence)? By contrast, how much is driven by other factors (such social or cultural fads or pressures)?