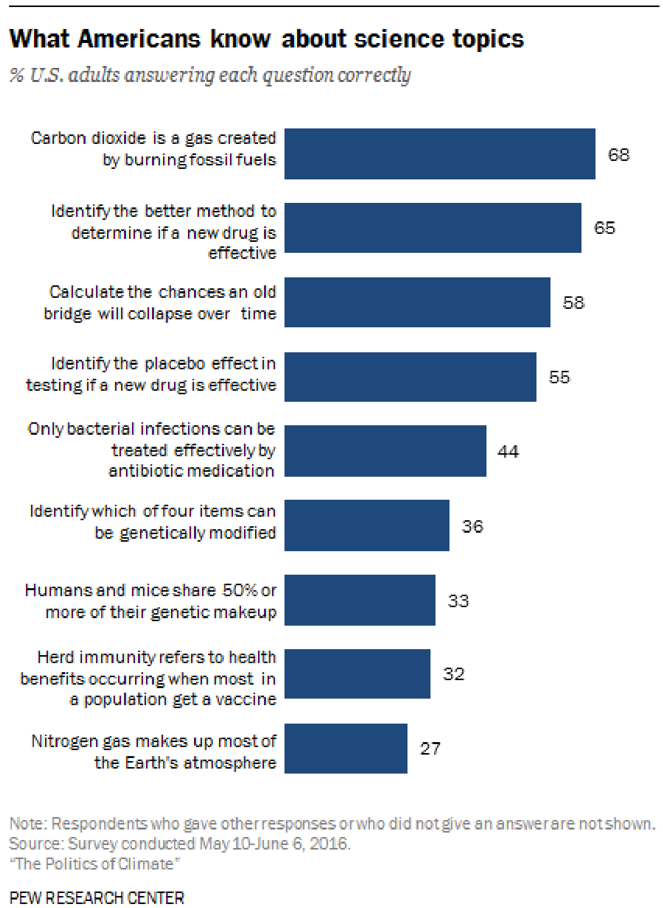
SCIENTIFIC REASONING: A HISTORICAL AND PHILOSOPHICAL INTRODUCTION

Welcome! This is a class about the nature of **scientific reasoning.** In this introductory lesson, we'll be focusing on answering the questions:

1. What does it mean to study the "history and philosophy of science"? How does this differ from other ways of studying science?
2. Why should scientists (or anyone!) bother studying history and philosophy of science?
3. What exactly is a scientific theory? A scientific mosaic?
4. What are some ways in which the scientific mosaic changed over time?

In future classes, we'll be looking more closely at questions concerning the **scientific method(s)**, the process of **scientific change,** the possibility of making **progress** in science, and the ways in which we might distinguish science from "non-science" (or **pseudoscience).**

BACKGROUND



Science touches almost every part of our current lives. Increasingly, many of our jobs require detailed knowledge of science and technology, whether this be medicine, physics (engineering), computer science, statistics, psychology, or any number of other areas. Our personal lives and choices are also increasingly guided by "science" says (or, at least, our best interpretation of what it says!). Beliefs about epidemiology, for example, have guided many people's responses to the COVID-19 crisis, just as beliefs about medical science guide our choices about medical treatment and our beliefs about nutrition science guide our choices of the food we eat. Political choices are also increasingly guided by beliefs about what is supported by various sciences, such as climate science and economics. Finally, beliefs about psychology help drive the educational choices we make for our children (and for ourselves), while beliefs about sociology drive our responses to social problems (and what we think the causes and solutions to these problems might be).

For all these reasons and more, most of us have a vested interest in reasoning *correctly* about science. That is, we want our choices to be guided by "legitimate" scientific research, and not simply by passing fads. Moreover, there are reasons to think that we (as humans) are not always as good at this as we might hope. To see this, just reflect on the (sometimes radical) changes that have occurred within the "scientific consensus" just within the last 100 years or so, especially in the sorts of areas that many people rely on to guide their choices. So, for example, new "weight loss" diets (nearly all proposed by some "scientist" or other) have appeared regularly, even as Americans (like other citizens of most other rich countries) have become, on average, much heavier. This is not to say we haven't learned new things about nutrition over this time—it's just that it's not always obvious to "consumers" of science how to sort the wheat from the chaff.

In this class, we'll be attempting to figure what, if anything, "makes" a certain theory scientific. As we'll discover, this isn't as easy as we might hope. Among other things, we'll discover that scientific theories (unlike the theorems of mathematics) can never be *proven* to be true, but that this does NOT mean we can't talk about better or worse theories.

*Questions: (1) Can you think of a time in which you changed the way you did something because you found out about a scientific discovery? (2) Can you think of an instance in which something you *thought* was supported by "science" turned out not to be?*

WHY STUDY THE HISTORY AND PHILOSOPHY OF SCIENCE?

The demand for certainty is one which is natural to man, but is nevertheless an intellectual vice. If you take your children for a picnic on a doubtful day, they will demand a dogmatic answer as to whether it will be fine or wet, and be disappointed in you when you cannot be *sure. The same sort of assurance is demanded, in later life, of those who undertake to lead populations into the Promised Land. "Liquidate the capitalists and the survivors will enjoy eternal bliss." "Exterminate the Jews and everyone will be virtuous." "Kill the Croats and let the Serbs reign." "Kill the Serbs and let the Croats reign." These are samples of the slogans that have won wide popular acceptance in our time. Even a modicum of philosophy would make it impossible to accept such bloodthirsty nonsense. But so long as men are not trained to withhold judgment in the absence of evidence, they will be led astray by cocksure prophets, and it is likely that their leaders will be either ignorant fanatics or dishonest charlatans. To endure uncertainty is difficult, but so are most of the other virtues. For the learning of every virtue there is an appropriate discipline, and for the learning of suspended judgment the bet discipline is philosophy.—Betrand Russell*[i]

There are a variety of ways in which one might study scientific reasoning. For example, nearly all of us have taken a class in either the **natural sciences** (physics, chemistry, biology, etc.) or **social sciences** (economics, psychology, sociology, etc.) at some point in our lives. These classes often do an excellent job in introducing (some of) the methods and ideas that are used within these particular sciences. However, they offer only a limited picture of "scientific reasoning" as a whole for at least two reasons: (1) they deal only with one very particular domain of science, and (2) they deal only with this science *as it is currently understood and practiced.* For example, introductory courses in specific sciences don't generally focus on *why* certain methods and theories were adopted, or what came before them. That is, they tend to overlook the processes and principles that drive *scientific change.*

In this class, by contrast, we'll be thinking a lot about scientific change, and comparatively less about the details of any individual science. This will also to present a "big picture" view of science's role in our lives. Our investigation will be both historical and philosophical (and often, both at once!). Here, "history of science" does NOT mean a history of individual scientists or of scientific institutions (so, no biographies of Einstein, or stories of how the first computer was made). Instead, we'll be thinking primarily about the history of *scientific theories***,** and in particular the process by which theories that experts *used* to adopt were abandoned, and new theories were adopted in their place. The "philosophical" part of our investigation means we'll be focused on very general questions about *why* and *how* this happened. For example: What does it mean for a theory to supported by evidence? What general reason do we have for thinking that new scientific theories represent progress over the old theories? And finally, are there are some theories that just are NOT scientific, even if they were/are popular?

Why should I care? One might study history and philosophy of science for any numbers of reasons. In one sense, it's fairly similar in scope to many other history and philosophy classes, in that it gives us a chance to think about something that is a big part of our lives ("science") in a detached, critical way. This, in turn, might help us make better decisions. What about if you are a practicing scientist, however? Will studying history and philosophy of science help you do *better* science? Unfortunately, the answer here is: probably not, at least if you're expecting things like new technologies or fancy mathematical techniques. To the extent that history and philosophy science can lead to better science, its often by uncovering the role of certain *assumptions* that are made within a scientific domain, which then allows these assumptions to be challenged. Many of the great philosopher-scientists of the past 500 years—from Rene Descartes to Isaac Newton to Albert Einstein—began their work with *philosophical* reflections on the weaknesses of the theories adopted by their contemporaries, which eventually allowed them to propose alternatives to these theories. Today, these sorts of debates continue to occur at the frontiers of science, from quantum mechanics to statistics and machine learning to genetics. As a rule of thumb, if/when "philosophers" actually figure out how certain types of problems are to be solved, these problems then become the domain of practicing scientists.

Questions: Which classes, books, etc. have made the biggest difference (so far) in the way you've thought about science.

SCIENTIFIC THEORIES AND SCIENTIFIC MOSAICS

We just said that this class will involve studying scientific theories and scientific mosaics. Here's what we mean by these terms:

- A **scientific theory** is simply a set of propositions (or "statements" or "sentences") that attempt to describe something. Famous examples include Darwin's theory of evolution by natural selection, the theory of continental drift, Newton's theory of gravity, Freud's theory of psychoanalysis, Keynesian economics, etc.
- A **scientific mosaic** is the set of all theories accepted by the scientific community at a given point in time. Basically: what theories are taught in introductory textbooks in high school and college? Which theories form the basis for PhD dissertations in the field, and lead to research projects that receive funding.

Extended Example: Physics and Astronomy. To begin our investigation of scientific theories and mosaics, it will help to begin with a more concrete example of how these theories might. We'll start with a standard example—the case of the planets and of gravity. Let's begin with an observation that *lots* of humans noticed *a long time ago* (and left regular records of):

- **Observation:** When we look at the night sky, most of the bright objects we see (call them *stars*) move in regular motions. However, there are a few (the "wanderers" called *planets*) that move through the sky in odd, circuitous motion.
- **The Question:** Why do the planets behave this way?

Many of the earliest examples of what we've above called scientific theories were formulated in large part to answer this and related questions. While we can't go through every theory, we CAN think about which sorts of theories gained widespread acceptance among university faculty and practicing scientists. For example, what theories were taught in a place like Oxford University (which has long been a center of scholarship in the English speaking world) in 1420 CE? In 1720? In 2020? In the next few sections, we'll take a closer look at this.

Question: Can you give some examples of theories (in any part of science) that make up part of the current "scientific mosaic"?

THEORY 1: ARISTOTLE'S THEORY OF NATURAL MOTION (~300 BCE TO 1600 CE).

Before the "Scientific Revolution," most academic work in Europe concerning "natural science" was based on the ideas of Aristotle[ii]. In astronomical theories of the period, the following propositions played especially central roles:

1. There are five basic **elements**: earth, air, fire, water, and quintessence. Things on earth are made of the first four, while heavenly bodies like planets and stars are made of quintessence.
2. Each element has its own **natural motion** determined by its **essence**. Earth and water for instance, always seek the center of the universe, while air and fire go toward the sky (unless, of course, this natural motion is interfered with). The stars and planets were made of *quintessence,* which moved in a circles (the most perfect motion).
3. From the above, we can conclude that the **Earth is the center of the universe**, since we can see this is where all the earth and water ended up!
4. This was eventually developed by Ptolemy into an astronomical theory with a stationary earth in the center of the universe and planets and stars circling around it. The planets irregular motions were due to their **epicycles** (their "circles within circles").

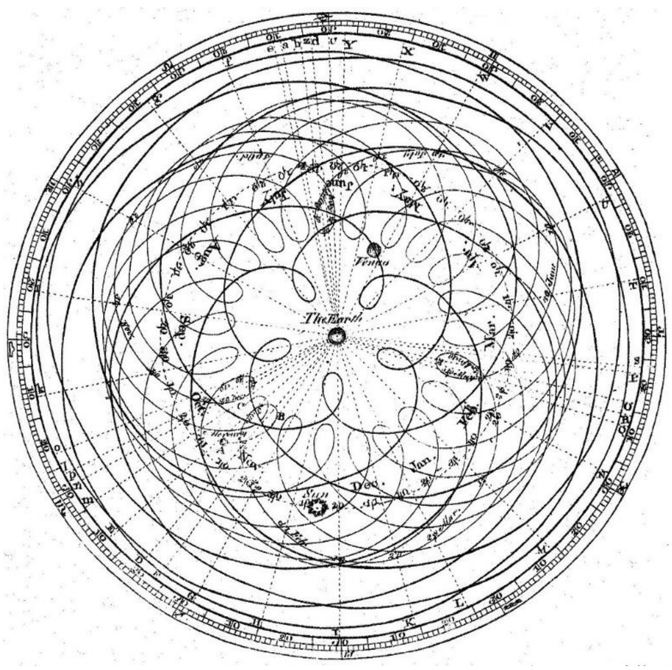


Figure 1a: Ptolemy's model of the universe placed the Earth in the center, while everything else revolved in circular orbits around it (image from Wikipedia).

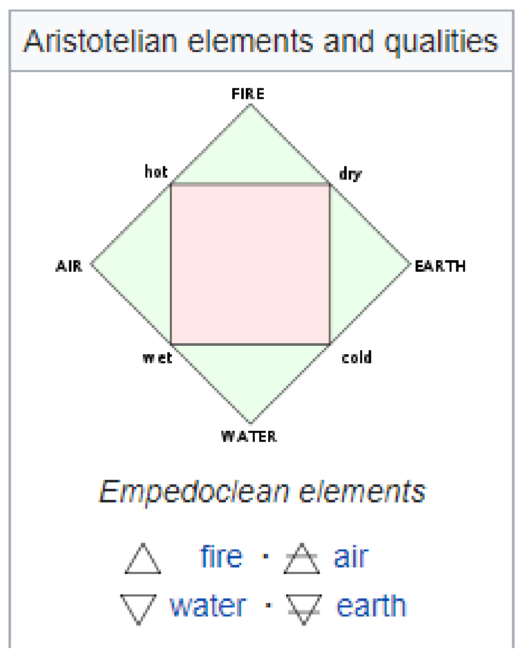


Figure 1b. Aristotle's four elements (Wikipedia), together with their natural direction of motion. Not displayed here is the heavenly element "quintessence", the natural motion of which is a circle.

Other pieces of the mosaic (in 1420). Aristotelian physics and Ptolemaic astronomy formed something like the "center" of the scientific mosaic for both Christian and Islamic Europe, just as they had for the Roman empire. Other pieces of the mosaic (that is, other theories) varied somewhat according to the time and place. In general, though, most scholars of the period accepted some sort of **astrological theory** (i.e., a theory describing how the motions of the heavenly bodies could predict and determine aspects of human life) and a theory of **natural theology** (i.e., the natural world revealed attributes of God and vice-versa). These were part of the science of the day! The theory of the four elements was also applied to human bodies (and even to human psychology) in the **"humoral medicine"** by people such as Hippocrates, Galen, Avicenna, and others. Ideas such as "bloodletting" (to get rid of whichever of the humors was excessive) followed naturally from this. Finally, there are a few pieces of the mosaic that might be more familiar to contemporary scientists, including **Euclidean geometry** and **(Aristotelian) formal logic.**

Question: In many cases, theories that are abandoned by the scientific community still "live on" in other forms. Can you think of any ways that theories from this "old" mosaic still influences the way we think or act?

THEORY 2: NEWTONIAN MECHANICS (~1700 TO 1910)

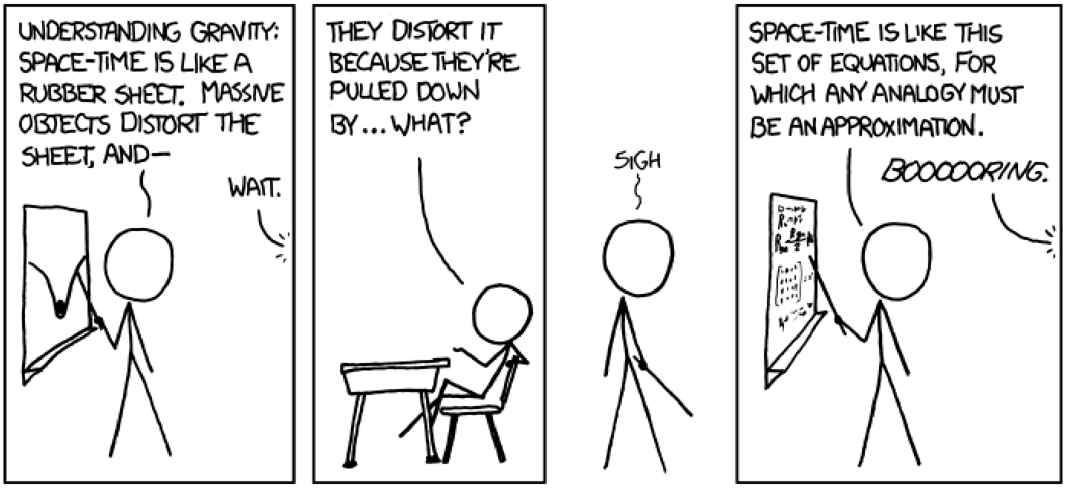
Building upon work by people such as Copernicus, Galileo, Descartes, and Kepler, Isaac Newton (1643-1727) proposed a physical theory ("Newtonian mechanics") that differed radically from that of Aristotle. Newtonian mechanics, together with his law of gravitation and new mathematical tool (of calculus), would become the center of the scientific mosaic for almost 300 years. Some key propositions:

1. Massive bodies do NOT have "natural motions." Instead, they follow the **law of inertia,** and remain their current velocity and direction unless acted on by an outside force.
2. One of these forces moving bodies around is **gravity.** This invisible force "pulls" all massive bodies toward one another according to the following equation: $F_G = G\frac{m_1 \times m_2}{d^2}$. Don't worry about the math here 😊. The basic idea is that strength of this force depends only TWO things: how massive the bodies are, and how far apart they are.
3. The **elliptical orbit** of the earth around the (much more massive) sun is due to gravity, in exactly the same way as the motion of a fallen apple toward the Earth (which is, in turn, much more massive than the apple) is due to gravity.

Other parts of the mosaic (in 1720). In the "popular" history of the Scientific Revolution that many people are taught, it often seems as if Newton's mechanics, optics, and calculus suddenly took us to modern science in one giant leap, and everything since has just been cleaning up the edges. This couldn't be further from the truth! Through most of the 1700s and much of the 1800s, many parts of the old mosaic still remained in place with only minor changes, including humoral medicine, natural theology, astrology, and even alchemy (all of which Newton himself dabbled in!). There were also new theories (such as the **phlogiston theory of heat**) that have long since been superseded. Finally, social sciences and economics were still in their infancy. As master of the Mint, for example, Newton pursued a policy based on **mercantilism** (an economic theory according to which a country can maximize national wealth by hoarding precious metals). In the centuries following Newton, many other areas of science (notably psychology, sociology, and economics) offered theories modeled after Newtonian, where "laws of nature" described the function of certain "forces."

Question: Newton, together with many of his contemporaries, was highly religious, and saw no qualitative difference between questions of religion and questions of science. Nevertheless, some scholars have argued that the widespread adoption of his theory helped (in the long run) pave the way for a scientific mosaic in which religion all but disappeared. What do you think of this?

THEORY 3: GENERAL RELATIVITY (~1920 TO THE PRESENT)



Teaching general relativity. From xkcd.com

The final theory we'll be talking about is due to Albert Einstein, who revolutionized physics in the early 20th century. Einstein's theory of general relativity is mathematically complex, but we can focus on a few key propositions to highlight its contrast with Newton's theory:

1. According to **special relativity,** the speed of light in a vacuum is set at an *absolute value,* regardless of your frame of reference (i.e., no matter how fast you are moving in whatever direction). This leads to weird results, like the fact that rate with time is passing in some place will be *relative* to your own position.
2. Einstein's explanation of the **photoelectric effect** helped lay the ground for the **wave-particle theory of light** and for **quantum mechanics.** These contradicted both Newton's particle theory of light, the later wave theory of light, and Newton's idea that physics involved fundamentally *deterministic* (as opposed to *statistical)* laws.
3. According to **general relativity,** there is no force called gravity that "pulls" massive bodies together. Instead, massive bodies "curve" space-time around them, which distorts the movements of *other* bodies that move nearby.
    a. Analogy: Consider a bed (a two-dimensional surface) with a bowling bowl dropped in the center of it. The bowling ball creates a curvature in the surface. If you now roll another, smaller ball near this, its path will be affected by this curvature.

One important thing to note here: according to this theory, the Newtonian mechanics that many of us learn in school (and may even use at our jobs!) is incorrect. There is simply *isn't* any force called "gravity" of the sort that Newton's equation described. Moreover, the theory also suggests that many of the other theories we've been taught (such as Euclidean geometry) may not actually apply in the way we think (according to General Relativity, our world is NOT a Euclidean world where the interior angles of triangles sum to 180 degrees). However, these older theories are still useful in many cases, especially since they are often easier to apply than is general relativity.

The current mosaic. This theory, together with **quantum mechanics** and **Big Bang cosmology,** form the basis for much of the current scientific mosaic as it relates to physics and astronomy. Other fundamental theories in the mosaic including the **theory of evolution via natural selection,** Mendel's theory of the **gene,** and the **atomic theory of the elements.**

Question: What are some of the other theories form a part of our current scientific mosaic?

QUESTIONS FOR REVIEW

To come…

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[i] Bertrand Russell, "Philosophy for Laymen," *Universities Quarterly* 1 (1946): 38–49.
[ii] For a detailed introduction to Aristotle's physics, see Istvan Bodnar, "Aristotle's Natural Philosophy," in *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, Spring 2018 (Metaphysics Research Lab, Stanford University, 2018), https://plato.stanford.edu/archives/spr2018/entries/aristotle-natphil/.