Chapter 7: Intro to Scientific Reasoning

A Little More Logical |Brendan Shea, PhD (Brendan.Shea@rctc.edu)

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2 THOUGHT QUESTIONS

1. How have advances in science affected your life?
2. What is your favorite area of science (or medicine)? Do you have a favorite scientist?
3. How much trust do you have in "science" as an institution? Why?

3 SCIENTIFIC ARGUMENTS

Scientific reasoning a huge role in almost every part of our day-to-day lives. Among other things, the ability to understand and evaluate scientific arguments plays a huge (and ever-increasing) role in decisions about what we eat, which medical treatments we use, which products we buy, how we parent/exercise/shop, and even our beliefs on which political proposals are most likely to improve things (and which are most likely to make them worse). These arguments concern everything from physics (nuclear power, space travel), biology (genetically modified crops), psychology (parenting, "management" techniques), and economics, just to name a few different areas.

3.1 THE BASICS

Logicians and philosophers of science (many of whom were scientists themselves!) have spent a lot of time thinking and writing about "how science works." Not surprisingly, they don't all agree on everything. However, there are a number of key concepts which *most* of them agree are central to understanding scientific reasoning:

Explanations: Brief Review. As we discussed earlier in class, an **explanation** is a set of two or more statements, one or more of which (the explanans) are claimed to be the reason/cause of the other (the explanandum). In this sense, they resemble arguments (with premises and conclusions). However, unlike the conclusion of an argument, we already *know* that the explanandum is true. So, when Julie offers the explanation in the example below, she is trying to explain *why it is* that she didn't do well on her math test. Of course, this explanation may or may not be the *correct* explanation—perhaps the real reason that Julie didn't do well is because she didn't attend class regularly, or something like that. For example:

- Explanans 1: Julie didn't sleep well last night.
- Explanans 2: Julie has a hard time concentrating when she doesn't sleep.
- Explanandum (what is to be explained): So, Julie did poorly on her math test today. (We already knew this was true—we are trying to figure out why it happened.)

What is a (Scientific) Hypothesis? There are many facts for which the explanation is not obvious:

1. My car did not start this morning, after having trouble earlier this week.
2. I went to a new seafood restaurant last night, and woke up with a strange rash this morning.
3. Joe Biden won the 2020 election.
4. The average surface temperature of the earth is higher now than it was 50 years ago.
5. Killing adult humans for fun is morally wrong.

In our attempts to explain these facts, we can propose tentative explanans, called **hypotheses:**

1. The battery on my car has finally died.
2. I am having an allergic reaction to shellfish.
3. Women, minorities, and younger voters turned out a higher rate than men, whites, and older voters.
4. Increased carbon dioxide emissions have caused a greenhouse effect, which is "trapping" heat near the earth.
5. It is wrong to deprive a person of a "future like ours."

Among other things, scientific reasoning involves attempts to confirm or falsify various hypotheses (though science also involves activities such as measurement, which may not involve directly testing hypotheses). In many cases, scientists consider *multiple* hypotheses that might explain a given set of facts, and use experiments and observations to figure which hypothesis, if any, is the correct one. (As the above examples show, though, not all hypotheses involve scientific reasoning).

[Question: Give an example of something that you think needs to be "explained." Now, propose at least two different hypotheses that might explain it).

3.2 The Hypothetical Method: Deduction and Induction

The **hypothetical method** is commonly used both in science and in everyday life. It has four steps, which involve both deductive and inductive reasoning. I've used Darwin's theory of evolution by natural selection as an example here, since this is undoubtedly one of the scientific theories people are most familiar with, and which has featured in many arguments over the role of science in education and policy:

- **Step 1: Clearly identify the explanandum, or the fact that you want to explain.** Example: Organisms are generally well-suited for their environments. A sparrow's wings allow it to fly quickly over short distances (and change direction rapidly to avoid predators), a penguin's fins allow it swim, and a goose's wings are ideal for long-distance flight.
- **Step 2: Formulate a hypothesis.** Example: Organisms have a common ancestor, but have been shaped into different species by natural selection. At some point in the distant past, there was a

common ancestor of geese, sparrows, and penguins. The descendants of this common ancestor ended up living in different environments, with very different selective pressures.

- **Step 3: Deduce implications or predictions of the theory.** Example: If evolution via natural selection is true, the fossil record should show gradual change. In some general sense, bird fossils found in era B should be "intermediate" between the older fossils of A and the younger fossils of C.
- **Step 4: Test the implications.** If the predictions are correct, the hypothesis is confirmed, which provides *some evidence* to think the hypothesis is true. This is the inductive part of the hypothetical method. Example: Go check to see whether this is in fact what the geological record shows.

[Question: Give an example of a time that you "tested a hypothesis" in your personal life. Did you go through all four steps laid out above? Did you end up accepting or rejecting the hypothesis]

When using the hypothetical method, there are a number of key points to keep in mind:

1. **You can't deduce a hypothesis from the facts.** The deductive part of the hypothetical method involves deducing *predictions* from the *hypothesis*. It is important to remember that this does NOT work the other way around: one cannot simply deduce a hypothesis from one what has observed. This is because any worthwhile hypothesis must always go "beyond" what you already know, and suggest *additional* tests or experiments. For example, if a patient has lung cancer, a physician cannot simply assume "Oh, he or she must have been a smoker." This would be a hypothesis, which would need to be tested further.
2. **The hypothetical method is often the *only* way of finding explanations.** Formulating a hypothesis and deducing implications (that you can then check) is the only way to "guide your search" for a true explanation. Without a hypothesis, you would have *no idea* of what sorts of facts might be relevant to explanation. This relates to the previous point: science does not precede simply by recording the facts and generalizing from them. Instead, scientists need to decide *ahead of time* which hypotheses they want to test, and then consider whether the evidence supports these hypothesis.
3. **Determining whether a hypothesis is FALSE is often much easier than determining whether it is TRUE.** If an application of the hypothetical method produces an incorrect prediction (as often happens), this means that either the hypothesis was false, or one of your other assumptions (e.g., concerning the accuracy of your test) was false. Even ONE false prediction is enough to do this. By contrast, it can often require *many* successful predictions (in a wide variety of situations) before we are willing to say a hypothesis is likely to be true, or that it is the *best* explanation for the phenomena in question.

[Question: My bet is that most of you have taken a science class or two, and some of you may even do "science" as part of your job. Besides the points laid out here, what are some common "mistakes" that you think people make about hypothetical reasoning?]

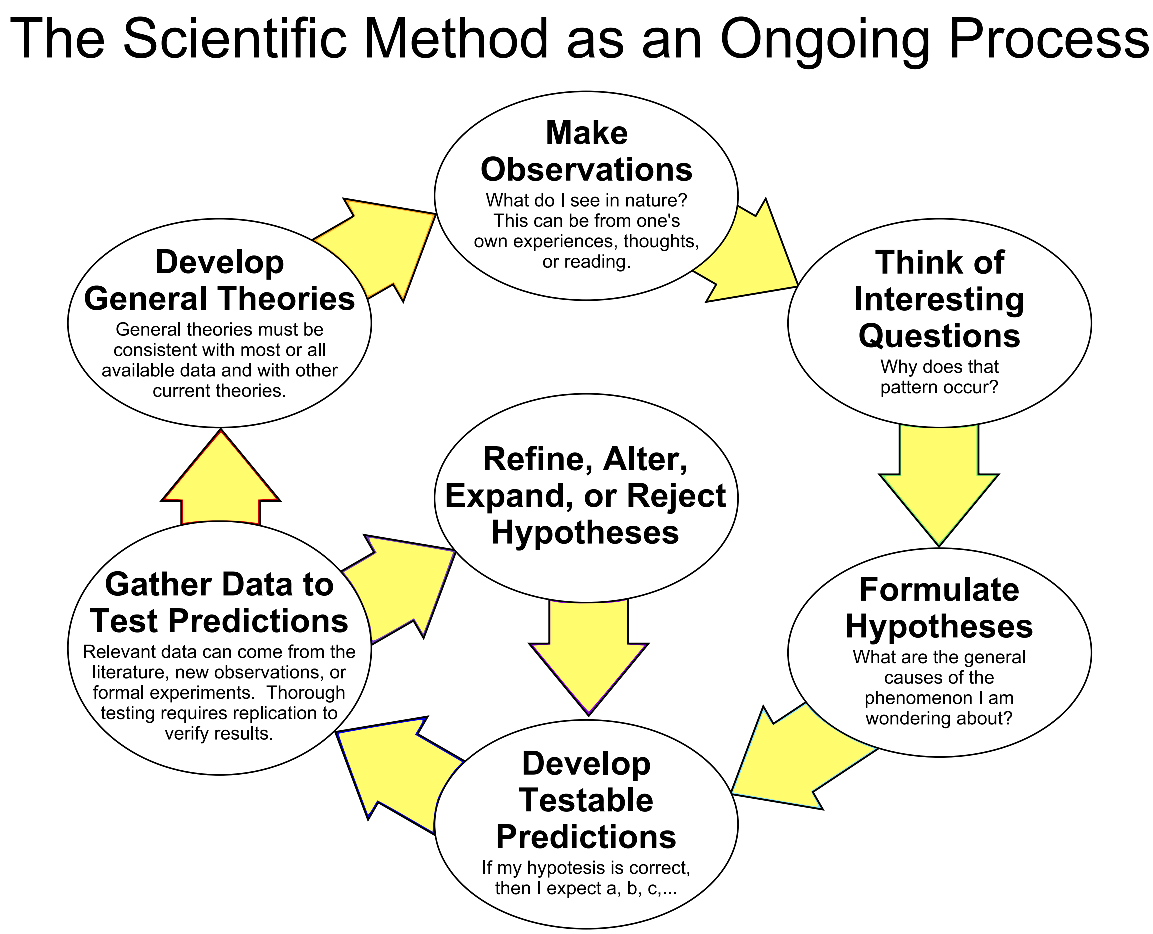

Figure 1 One account of the scientific method (from Wikimedia Commons).

3.3 Falsification versus Confirmation

Point 3 (above) said two things: (1) If a hypothesis makes an incorrect prediction, we can be (deductively) certain that one of our assumptions was FALSE, and (2) if a hypothesis makes a correct prediction we DON'T know that it is true, even though this may provide (inductive) support for the hypothesis. So, there is an asymmetry between falsity (easy to establish) and truth (much harder to establish). So, for example, let's suppose Bob and Belinda are roommates with Betty. Betty never goes out during the day, which puzzles Bob and Belinda. Bob and Belinda propose the following hypotheses to explain this fact:

- Bob's Hypothesis: "Betty is a vampire." Implications: "If we take Betty into sunlight, she will explode. She may or may not have hair lying around her room"
- Belinda's Hypothesis: "Betty is a werewolf." Implication: "Betty will have lots of loose hair laying around her room. She won't explode in sunlight."

Suppose that Bob drags Betty outside and she does NOT explode. Simultaneously, Belinda looks around Betty's room, and does find lots of loose hair. The hypothetical method allows us to conclude that Bob's hypothesis is FALSE. By contrast, we still can't determine whether Belinda's hypothesis is true. It is important to remember that there will always (always!) be hypotheses that are not considered. For example, perhaps Betty works a night shift at the local hospital, and sleeps during the day. However, because Bob and Belinda aren't considering this hypothesis, they can't test it.

3.4 Hypothetical Reasoning in Science: An Example

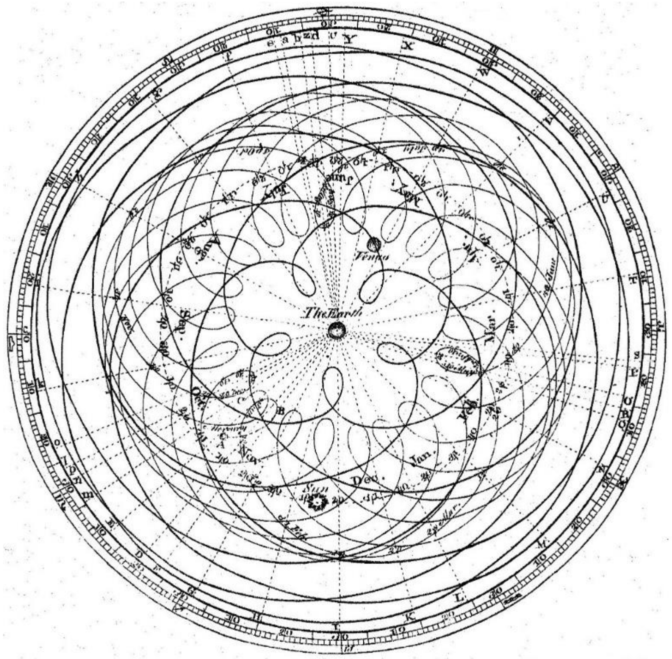

Figure 1a: Ptolemy's model of the universe placed the Earth in the center, while everything else revolved in circular orbits around it (image from Wikipedia).

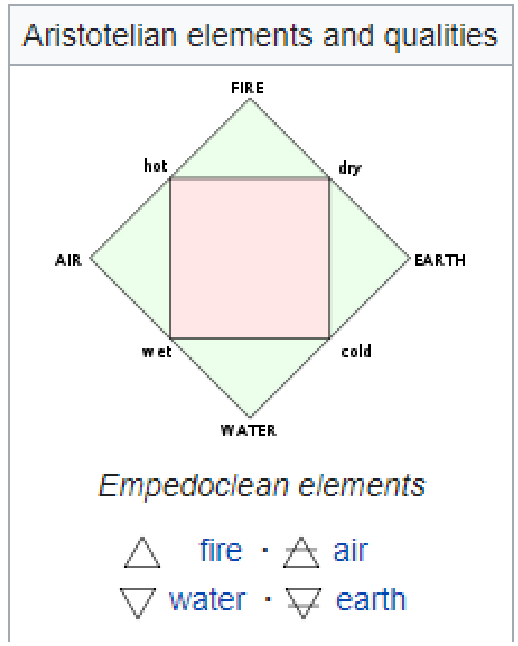

Figure 1b. Aristotle's four elements (Wikipedia), together with their natural direction of motion. Not displayed here is the heavenly element "quintessence", the natural motion of which is a circle.

Hypothetical reasoning plays a huge role in the history of science. One problem of historical interest concerns the fact "When observed from Earth, planets like Mars, Venus, Mercury, and Jupiter appear to wander around the sky—that is, they sometimes appear to move backwards. This is very different from the way stars appear to move." Here are three historically important sets of hypotheses:

Hypothesis 1 (Aristotle): The planets orbit around a stationery Earth in circular orbits.

- Implication: The planets should NOT move backwards, but instead should always move in the "same direction" across the sky.
- Testing: The planets appear to move backwards, so the hypothesis is FALSFIED.

Hypothesis 2 (Ptolemy): The planets orbits around the stationery earth in circular orbits but some circle back in small "epicycles."

- Implication: The planets will sometimes appear to move "backwards" across the sky.
- Testing: The hypothesis is NOT falsified, since the implications agree with what we observe.

Hypothesis 3 (Copernicus): All of the planets orbit the sun, and the moon orbits the earth. The earth is not stationery.

- Implications: From our perspective, it will sometimes appear as if planets "wander" backwards and forwards.
- Testing: This agrees with observation. So, the hypothesis is NOT falsified.

Our problem is that both Ptolemy's hypothesis and Copernicus's appear to "explain" the data, especially for the first few decades after Copernicus proposed his theory. That is, both of the hypotheses can account for the fact that the planets appear to "wander" backward and forward through the night sky. What we need to do is figure out a **crucial experiment**. That is, we need to figure a particular experiment where Ptolemy's hypothesis says that we should get one result, and Copernicus's hypothesis says that we should get another result.

Galileo's Telescope. Galileo, a proponent of Copernicus's theory, built an early telescope, which allowed him to see things that earlier astronomers (such as Copernicus and Ptolemy) could not. This allowed him to carry out something like a crucial experiment to decide between Copernicus's and Ptolemy's hypotheses:

- Ptolemaic prediction: The earth is the center of the universe—everything orbits around it. So, observations through the telescope should NOT reveal moons orbiting other planets.
- Copernicus prediction: The earth is not the center of the universe, but it nevertheless has a moon orbiting around it. So, it is perfectly possible that other planets will have moons orbiting around them, which the telescope will enable us to see.

While observing Jupiter with his telescope, Galileo observed small "dots" that would pass across the face of the planet and then "disappear." This happened at regular intervals, and Galileo realized that these were moons orbiting the planet, in sharp contrast to what the Ptolemaic theory would have us believe. Galileo was also able to make successful prediction about the "phases of Venus"—his theory, unlike Ptolemy's, successfully predict which parts of Venus would be lit up by the sun at particular times. He concluded that Copernicus was right, and that the Earth was NOT the center of the universe.

It's important to note that Galileo was NOT the only scientist working on such matters at the time, and while his evidence was perhaps the best/strongest early evidence for Copernicus, he was far from alone. (This is almost always the case with science!).

"Saving" Falsified Hypotheses. Galileo's observations are now widely accepted as evidence in favor of the Copernican theory. However, this was not immediately so at the time, as many of Galileo's critics (for a variety of motives—religious, political, and plain old scientific disagreement) argued that either Galileo's observations were somehow corrupted/faked, or that he'd misinterpreted them.

[Question: While it's easy to look back down and think "Galileo's critics were clearly wrong!", some of the problems he encountered, such as the general fact that the scientific community is usually NOT quick to give up on established theories, are probably always going to be issues, for reasons both good and bad. Can you think of other cases were this happened?]

3.5 Review Questions

For each of the following explananda (i.e., things to explain), propose at least three potential hypotheses. Then, state an implication of each hypothesis that would allow you test your hypothesis.

1. You send your best friend a text. They usually respond promptly. However, it's now been eight hours and you still haven't heard anything.
2. You have a pet dog, Snoopy, that almost always greets you at the door when you come home. One day, Snoopy, does not greet you.
3. Your significant other, Sam, used to come meet you for dinner nearly every evening. For the last month, however, Sam has been "working late," and only meets you for dinner once or twice a week.
4. Your computer does not turn on when you press the power button.

5. You and your friend have been working for Professor B for the same amount of time. You've both received similar performance reviews. However, you were offered a promotion, while your friend was not.
6. You had a headache yesterday, which went away after you ate a large serving of Potato Oles. You suspect Potato Oles cured you.

4 SCIENTIFIC REASONING: CONFIRMING HYPOTHESES

The **confirmation** of scientific hypotheses by evidence is a matter of inductive reasoning. Each new observation or experimental result serves as a premise which can make our conclusion (regarding the truth of the hypothesis) either more or less likely to be true. With this general background, it is important to keep the following key points in mind:

- A hypothesis is a proposed **explanation** that goes "beyond" what we already know. Because of this, we do not (initially) know whether a hypothesis is true. As we conduct experiments and observations, however, we can begin to figure this out.
- A hypothesis is **confirmed** by evidence that gives us some reason to believe that this hypothesis is true. The fact that some particular evidence confirms a hypothesis does NOT mean that we have good reason to believe the hypothesis, all things considered. In order to establish this, we often need a large amount of high quality evidence.
- Confirmation comes in **degrees**. If a hypothesis is strongly confirmed by evidence, then that evidence gives us very good reason to believe the hypothesis. If the evidence only weakly confirms the hypothesis, by contrast, this might mean we need to go gather more data. There are many intermediate degrees of confirmation.
- A well-confirmed hypothesis is sometimes referred to as a scientific **theory** ("The theory of relativity," "The theory of continental drift," "The theory of gravity," and so on). This is *different* from the way we sometimes use the word "theory" in other contexts, where "theory" means something like a "guess."

How Confirmation Works. A hypothesis is confirmed by a given observation if and only if the following TWO criteria are met:

1. We don't already know that the hypothesis is false. Once we know that a hypothesis is false, no further data can confirm it. So, for example, since we now know that the earth revolves around the sun, the observation that "it sure doesn't feel like the earth is moving" does NOT confirm the hypothesis that "the earth really doesn't move."
2. The following inequality holds: "The probability that we would see these observations on the assumption that the hypothesis is true" is greater than "the probability we would see these observations on the assumption that some other hypothesis is true." In other words: if this hypothesis really were true, we'd expect to see this sort of thing. On the other hand, if it were false, this would be much more surprising.

The basic point: What matters for confirmation is making **surprising** predictions that turn out to be true. A hypothesis is NOT confirmed by predicting things that we already expected.

4.1 EMPIRICAL VS. THEORETICAL HYPOTHESES

An **empirical hypothesis** is a hypothesis whose truth or falsity can be directly observed. If we observe that the hypothesis is true, the hypothesis is very strongly confirmed. For example, suppose that we have the following explanandum: "My car has suddenly begun pulling to the left." Here are some empirical hypotheses:

- Empirical Hypothesis 1: My left front tire is flat.
- Empirical Hypothesis 2: My left rear tire is flat.
- Empirical Hypothesis 3: The axel rod on my car is broken.

Determining which one of theses hypotheses (if any) is correct can be directly observed (either by me or by a mechanic). Once we have done these observations, we can strongly confirm one of the hypothesis, while falsifying the others. Of course, we can't be *absolutely sure* of the truth of a hypothesis (perhaps I made a mistake in my observation, or maybe I'm dreaming). However, if two different mechanics tell me that my left rear tire is flat (and I can see that it is flat, as well), I have *very good reason* to believe to believe that hypothesis 2 is the correct one, while hypotheses 1 and 3 are not.

Many hypotheses of scientific interest (including most of the important ones) are NOT empirical hypothesis, since they involve things (electrons, distant stars, viruses, the past, mental states) that CANNOT be directly observed. Hypotheses involving such unobservable entities or processes are called **theoretical hypotheses**. Theoretical hypotheses are confirmed or falsified by considering all of the evidence (as opposed to empirical hypotheses, which can essentially be confirmed or falsified by a single observation). The decision to adopt a theoretical hypothesis is a function of four interrelated factors:

1. Is the hypothesis **adequate**? That is, is it a good explanans for the explanandum that it was originally proposed to explain?
2. Is the hypothesis **internally coherent?** How "simple" is the hypothesis? Does the hypothesis require lots of "adjustment" to get it to fit the actual data (if so, that's bad)?
3. Is the hypothesis **externally consistent**? How well does it fit with other, well-confirmed theories in different areas of science?
4. A good hypothesis should be **naturalistic**, and should ideally avoid attributing things such as desires, intentions, or beliefs to the natural world (so, no gods or demons).
5. Is the hypothesis **fruitful**? If this hypothesis were adopted, would it suggest new hypotheses that could be tested? If we knew the hypothesis were true, would this allow us to do things?

Hypothesis confirmation is often **comparative—**we want to know which hypothesis (of the two or more that have been proposed) does better on these criteria. This means we need to be careful about assuming that our current working hypothesis is the "true" one; instead, we might say "it's closer to the truth than the others" or "it's our best explanation right now, and should be assumed until we find something better."

Theoretical Hypotheses: An Example: Suppose our explandandum is "The earth orbits the sun." Let's consider the following hypotheses:

- Theoretical hypothesis 1: There is an attractive force, gravity, that pulls massive objects like the earth and the sun together. [Since we cannot see gravity, this is a theoretical hypothesis, as opposed to an empirical one.]
- Theoretical hypothesis 2: Invisible demons are carrying the earth in a circle around the sun. [Again, we cannot observe the demons, so this a theoretical hypothesis.]

In this case, it is clear that Newton's theory of gravitation (hypothesis 1) is superior to hypothesis 2. While both hypotheses "explain" the phenomenon, Newton's theory is simpler (gravity is a force we already know about, while invisible demons would be something entirely new). It also fits better with the rest of physics, is more naturalistic, and is fruitful (since it allows us to predict how *other* heavenly bodies will move in response to gravitational forces). This doesn't mean, of course, that Newton's theory is entirely correct as a description of the universe. In fact, Einstein showed that Newton's theory *wasn't* correct, even though it worked well in certain sorts of settings (and quantum theory showed that Einstein wasn't correct, though he was closer than Newton, and so on).

4.2 Darwin and Paley: Evaluating Theoretical Hypotheses

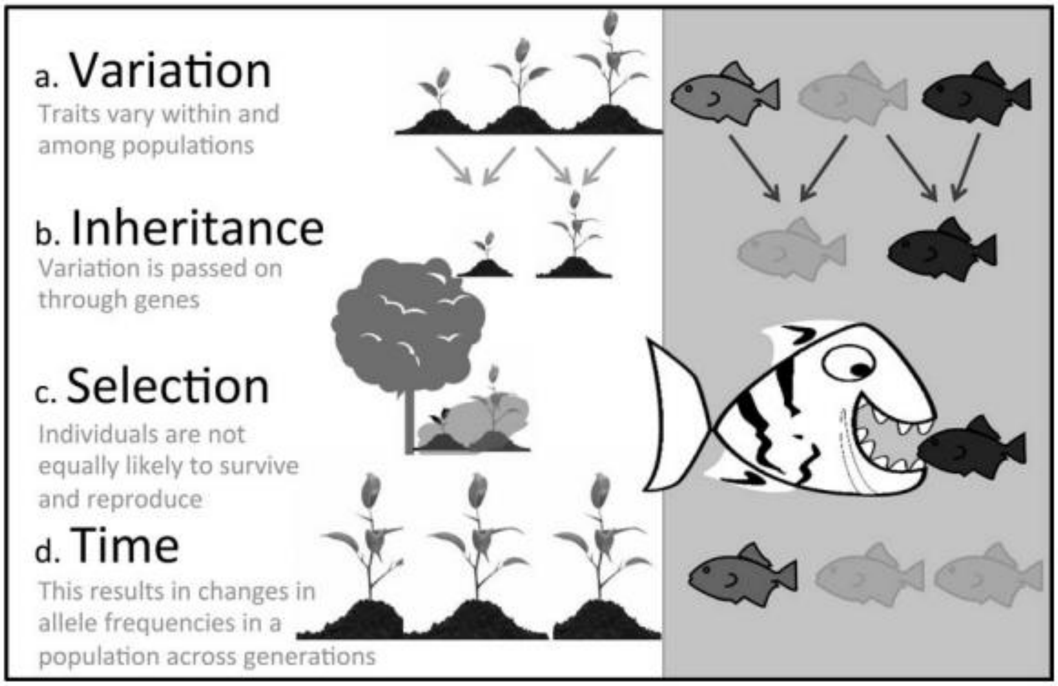

Figure 2 Evolution via natural selection (from American Biology Teacher, 2018).

To see how the evaluation of theoretical hypotheses works in practice, let's consider a "real world" case from the history of science: the comparison of Darwin's hypothesis of evolution by natural selection with William Paley's hypothesis of divine creation of individual species. We'll be considering only the evidence that was available to Darwin at the time that he wrote, with an eye toward showing *why* subsequent generations of biologists adopted his theory (and rejected Paley's). (*Note:* This is NOT intended to survey the modern debate concerning whether "intelligent design" should be taught in schools. The emphasis here is on understanding the historical debate.)

Background. Perhaps the best-known debate concerning scientific hypotheses is the 19th century argument over the origin of species. The explanandum could be described as follows "Organisms have complex adaptations that allow them to flourish in their environments." The two hypotheses of interest were:

- Hypothesis 1 (**Creationism**, defended by William Paley): "The first member(s) of each species was created by an intelligent designer. Species were specifically designed for the environments in which they live."
- Hypothesis 2 (**Evolution by natural selection**, defended by Charles Darwin, as well as by the less-famous Alfred Russell Wallace): "All organisms descended from a small number of ancestors. Adaptations are caused exclusively by the facts that (1) there is random variation among the traits of a population, (2) there is non-random selection amongst traits (i.e., organisms with certain traits are more likely to survive and reproduce), and (3) offspring inherit traits from their parents."

Both of these hypotheses are theoretical rather than empirical, since we cannot *observe* the historical origins of the various species. So, we need to consider the criteria for assessing theoretical hypotheses just introduced.

Adequacy. The first (and most important) criterion is adequacy. A (very) rough way of looking at this: the hypothesis that explains the most facts "wins". Some things that Darwin could explain that Paley could not include the following:

1. The fossil record showed gradual change, which Darwin's theory definitely predicted. Paley's theory was compatible with this (the creator *could* have done things this way), but his theory gave no reason to expect it.
2. There were many cases in which the experts disagreed on what counted as "members of the same species". This was to be expected on Darwin's theory, since species emerged slowly over time, and we would expect this sort of "gradualism." On Paley's theory, it was surprising, since each species was created entirely separately.
3. Many organisms have rudimentary organs that serve no apparent purpose. Again, Darwin's theory predicted this (since these organs might be remnants of things that *did* matter to distant ancestors of the organism), while Paley's did not (Why would the creator make useless organs?).
4. Non-native (or "invasive") species are often more successful in an environment than native species are. This would be surprising if organisms were "custom-designed" for their environment, as Paley had argued. It's exactly what we would expect on Darwin's theory however.
5. Long-lasting geographical barriers (such as the Panama isthmus) often separate entirely different species, even if the environments (the oceans on either side) are almost identical (and could support the same species). If species were custom-designed (Paley), this would be very surprising, since there would be no *reason* for a creator to do that (why design two species for the same environment?). The random aspects of the evolutionary process, by contrast, would account for it.
6. Other facts: Darwin also discussed the structural similarities (in skeletal structure, etc.), the cross-species similarities between embryos and fetuses (mammalian embryos/fetuses have non-functional "gills"), all of which seemed difficult to explain if each species was designed independently, but which might be expected if natural selection was responsible (since natural selection always has to "work with what is already there," and can't design new organisms from the ground up).

None of these predictions *falsified* Paley's theory: after all, it is entirely possible that a creator might have wanted to design living things in this way for some (unknown) reason. However, Darwin argued that his theory, unlike Paley's, provided a good *explanation* of why they were true. On Darwin's theory, these were the sorts of things that one would *expect* to see.

Internal coherence means that the parts of a theory "fit together" and the hypothesis does not require "tinkering" to make it work correctly. Darwin's theory was highly internally coherent. It required only a few, simple assumptions, such as "Organisms resemble their parents, but differ in small ways. The most fit organisms will reproduce at a higher rate than less fit organisms." Paley's theory was not (as) internally coherent, and required many small "adjustments" to make it work OK. "The creator usually created the best organisms for each environment, but sometimes did not. The creator made the fossil record so that it looked like evolution was true, even though it wasn't. The creator sometimes gave organisms rudimentary organs, even though these organs were useless." So, while Paley's theory seemed simple to people who were NOT biologists, those trying to apply it found that it required lots of (fairly unintuitive) claims about how the intelligent creator would behave.

A hypothesis that is **externally consistent** will fit with well-confirmed hypotheses in other areas of science. Darwin's theory was highly externally consistent. It fit with recent discoveries in geology (e.g., rock formations suggesting the earth was much older than 6,000 years), physiology (e.g., the development of human and mammalian embryos), and zoology (e.g., the fact that zoologists often could not agree on what counted as a new "species"), and biogeography (e.g., which species were found in which geographic locations). Later, Darwin's theory would fit well with developments in chemistry (e.g., studies of DNA). Paley's theory either contradicted other well-confirmed hypotheses (e.g., in the case of geology) or strongly suggested that they were incorrect (e.g., in the case of physiology or zoology). It didn't appear to be **naturalistic**, at least if the creator was identified with a divine figure.

A hypothesis **fruitful** to the degree that it opens up new areas for research, and suggests new hypotheses that can be tested. Darwin's theory proved to very fruitful, even in the years immediately after his death. It quickly led to new hypothesis in paleontology (regarding the types of fossils that would be found) and eventually in genetics (regarding the existence of "genes" and DNA). In the twentieth century, it was central to the study of medicine (e.g., regarding the "evolution" of cancer cells, or of antibiotic-resistant pathogens) and many other areas. Paley's hypothesis was not fruitful—if we were suddenly assured that Creationism were true, this would tell us almost nothing about genetics, medicine, or paleontology.

CONCLUSION: According to the criteria we have adopted, Darwin's theoretical hypothesis was strongly confirmed by the evidence that he provided. This does NOT mean that Creationism is "falsified" (in fact, some philosophers of science have argued the theory is unfalsifiable, and thus might not qualify as "scientific" in the first place), but it does help explain why scientists have thought that there are good (inductive) reasons for preferring Darwin's theory to Paley's.

4.3 Review Questions

1. In your own words, explain the basic ideas behind each of the following theories:
    a. Darwin's theory of evolution via natural selection
    b. Paley's theory of "creationism"
2. Pretend that you are teaching a 12-year-old about the evidence for Darwin's theory. Explain ONE piece of evidence for the theory, using your own words.
3. What is one piece of possible piece of evidence that, if we observed it, would falsify Darwin's theory?
4. Do you think it would be helpful to teach high-school biology students about the "reasons" Darwin's theory was originally accepted? Why or why not?
5. Besides Darwin's theory, can you give some other examples of scientific theories that represented a major "change" in the way we thought about things? What sorts of evidence was used to confirm these theories?

5 Reading: The Necessity of Awe (Helen De Cruz)[1]

When a scientific paradigm breaks down, scientists need to make a leap into the unknown. These are moments of revolution, as identified by Thomas Kuhn in the 1960s, when the scientists' worldview becomes untenable and the agreed-upon and accepted truths of a particular discipline are radically called into question. Beloved theories are revealed to have been built upon sand. Explanations that held up for hundreds of years are now dismissed. A particular and productive way of looking at the world turns out to be erroneous in its essentials. The great scientific revolutions – such as those instigated by Copernicus, Galileo, Newton, Lavoisier, Einstein and Wegener – are times of great uncertainty, when cool, disinterested reason alone doesn't help scientists move forward because so many of their usual assumptions about how their scientific discipline is done turn out to be flawed. So they need to make a leap, not knowing where they will land. But how?

[1] Helen de Cruz, "How Awe Drives Scientists to Make a Leap into the Unknown," Aeon, 2020, https://aeon.co/essays/how-awe-drives-scientists-to-make-a-leap-into-the-unknown.

Figure 3 Awe. (Brendan Shea x Dall-E).

To explain how scientists are able to make this leap, the philosopher of science Bas van Fraassen in *The Empirical Stance* (2002) drew on Jean-Paul Sartre's *Sketch for a Theory of the Emotions* (1939). Sartre was dissatisfied with the major mid-20th-century theories about emotions (especially those by William James and Sigmund Freud) that treated emotions as mere passive states. You might *fall* in love, or be *gripped with* jealousy. It seemed that emotions happened to you without any agency on your part. Sartre, by contrast, held that emotions are things that we *do*. They have a purpose, and they are intentional. For example, when we get angry, we do so to seek a solution, to resolve a tense situation. Sartre wrote:

When the paths before us become too difficult, or when we cannot see our way, we can no longer put up with such an exacting and difficult world. All ways are barred and nevertheless we must act. So then we try to change the world.

The world that Sartre referred to is the world of our subjective experience. It is the world of our needs, our wants, our fears and our hopes. In his view, emotions transform the world like magic. A magical act, such as voodoo, alters the attitude of the practitioner to the world. Magical spells and incantations don't change the physical environment, but they change *our* world, by shifting our desires and hopes. Similarly, emotions change our outlook and how we engage with the world. Take Sartre's example of sour grapes: seeing that the grapes are unreachable, you decide, 'they are too sour anyway'. Though you didn't change the chemical property of the grapes in any way, the world has become a bit more bearable. Anticipating contemporary ideas about embodied cognition, Sartre speculated that physical actions help us to produce emotions. We clench our fists in anger. We weep in sadness.

Applying this idea to scientific practice, Van Fraassen argues that scientists draw on their emotions when dealing with new, bewildering ideas, especially those that sprout up during scientific revolutions. If the paradigm is faltering, scientists need to change the way they view the world – and this requires that they change themselves. Scientists need to transform both who they are and what they know. Only once scientists themselves are transformed in this way can they accept a theory that they originally thought outlandish or ridiculous.

There are a few problems with this theory. Van Fraassen doesn't specify *which* emotions can help scientists. Would it be sufficient to be intrigued or excited by a new theory, or to feel curiosity? Would anger at the failure of the old paradigm do the job? And it's not clear *how* scientists can use emotions to change their minds. Sartre seems at times to assume that we have our emotions under direct voluntary control. But this appears implausible, on the face of it. Surely not *all* our emotions are under our direct control?

One way to salvage the Sartre and Van Fraassen account is to propose that emotions are under our *indirect* control. We can't control our emotions directly, but we can engage in practices that, over time, help to shape how we emotionally respond to a variety of situations. And as for *which* emotion most helps scientists, I have a particular one in mind: awe.

In their classic account of awe, the psychologists Dacher Keltner and Jonathan Haidt characterise awe as a spiritual, moral and aesthetic emotion. In their view, all clear cases of awe have the following two components: an experience of vastness, and a need for cognitive accommodation of this vastness. You might feel awe for things that are physically large, but also for ideas that are conceptually vast. For example, at the end of the first edition of his *Origin of Species* (1859), Charles Darwin expressed awe for his theory of natural selection:

There is grandeur in this view of life, with its several powers, having been originally breathed into a few forms or into one; and that, whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved.

The need for cognitive accommodation makes you aware that there is a lot you don't know. You feel small, insignificant and part of something bigger. In this way, awe is a self-transcendent emotion because it focuses our attention away from ourselves and toward our environment. It is also an epistemic emotion, because it makes us aware of gaps in our knowledge. We can feel overwhelmed looking at the night sky, deeply aware that there is so much we don't know about the Universe. In one recent study, participants listed nature as their most common elicitor of awe, followed by scientific theories, works of art and the achievements of human cooperation.

The philosopher Adam Morton speculates that epistemic emotions play a crucial role in scientific practice. Imagine a scientist who knows the latest research techniques, and who is intelligent and analytical. If she lacks curiosity, awe and other epistemic emotions, she won't have the drive to become a good scientist, who can change her mind on the basis of evidence, explore new hypotheses or pay attention to unexpected results. As Van Fraassen argued, to change the field or accept radical changes in it, you need to alter your outlook on the world. Awe can do this. It focuses attention away from yourself and makes you think outside of your usual thought patterns.

Many scientists have noted in their autobiographical writings how their sense of awe drove their scientific work. Here is the evolutionary biologist Richard Dawkins in *Unweaving the Rainbow* (1998):

The feeling of awed wonder that science can give us is one of the highest experiences of which the human psyche is capable. It is a deep aesthetic passion to rank with the finest that music and poetry can deliver. It is truly one of the things that make life worth living, and it does so, if anything, more effectively if it convinces us that the time we have for living it is finite.

The conservationist Rachel Carson identified awe as a source of resilience in difficult times. In an echo of Sartre's theory of emotions as a source of refuge, in 1956 she insisted that we should encourage children to maintain and develop their sense of awe so that it doesn't diminish over time:

What is the value of preserving and strengthening this sense of awe and wonder, this recognition of something beyond the boundaries of human existence? Is the exploration of the natural world just a pleasant way to pass the golden hours of childhood or is there something deeper? I am sure there is something much deeper, something lasting and significant. Those who dwell, as scientists or laymen, among the beauties and mysteries of the Earth are never alone or weary of life. Whatever the vexations or concerns of their personal lives, their thoughts can find paths that lead to inner contentment and to renewed excitement in living.

Empirical evidence suggests that awe plays a role in the appreciation of science. These studies provide a tentative glimpse of how awe and science relate, even though they focus on laypeople, and not (yet) on scientists themselves. Writing in 2018, the psychologists Keltner, Sara Gottlieb and Tania Lombrozo found that the tendency to feel awe (dispositional awe) is positively associated with scientific thinking in non-scientists. Participants with higher dispositional awe have a comparably better grasp on the nature of science, are more likely to reject Young Earth creationism, and also are more likely to reject unwarranted teleological explanations for natural phenomena. When awe is induced, people feel more positive toward science. One recent study showed participants a movie montage of the BBC TV series *Planet Earth*, containing sweeping vistas of waterfalls, canyons, forests and other awe-inducing views. Participants in a control condition watched humorous videos of cute animals engaged in capers and antics. Those who saw the awe-inspiring videos were more aware of gaps in their knowledge than those who saw the funny videos.

This suggests that eliciting awe would be good for scientific practice. How can we do that? The theologian and philosopher Abraham Joshua Heschel argued for the importance of awe in two short books, *Man Is Not Alone* (1951), and *God in Search of Man* (1955). Heschel thought that people are taking the world for granted, thereby losing their ability to experience it with depth and reverence. We have taken to a kind of complacency where we think that science can solve all our problems, without pausing to think about the marvels that science has revealed to us. 'Modern man fell into the trap of believing that everything can be explained, that reality is a simple affair which has only to be organised in order to be mastered,' he wrote. According to Heschel, awe and wonder are the antidotes.

Like Sartre, Heschel held that emotions are a kind of cognitive technology, things we do purposively to change the world. But Heschel (unlike Sartre) didn't think that the main transformative effect of emotions was to make an unbearable and conflicted world bearable. Rather, Heschel thought that emotions could help us to see the world not in flat, drab and purely instrumental terms, but as valuable for its own sake, filled with marvels. Deep knowledge, of the kind attained by profound scientific insight or, for Heschel, religious wisdom, requires that we see the world in these terms: as an end, beautiful in itself. And for that, awe is required.

How is awe evoked? Heschel argued that Jewish rituals are conducive to awe: there are blessings that orthodox Jews utter at particular occasions, for example, when you see a rainbow, or notice the first tenuous blossoms on fruit trees, or meet a wise person, or hear good news. These blessings are embodied physical actions that one performs to mark certain emotional states in response to the environment. The repetition of ritual practices trains our minds and bodies to respond with awe and wonder to the world around us. By uttering a blessing, you become more attuned to how precious and fleeting these things are. For Heschel, rituals are *not* a form of adjusting yourself to the world. They are the opposite: they are about *maladjustment*: 'Wonder or radical amazement, the state of maladjustment to words and notions, is therefore a prerequisite for an authentic awareness of that which is.' Conceived this way, Jewish rituals are an antidote to falling into ruts. They drive us out of our dull complacency, and help us to see the world in a new light.

While it is easy to see how rituals can help us instil awe in religion, it's not so clear how rituals would achieve the same thing in scientific practice. Heschel was skeptical that scientists could use ritual practices to induce awe: 'A scientific theory, once it is announced and accepted, does not need to be repeated twice a day.' This dismissal is too hasty. The rise of denialism about science indicates that a scientific theory isn't announced and accepted once and for all. Even a long-discredited theory such as flat Earth can resurge in the wake of misinformation campaigns.

There are already ritualistic elements in scientific practice that might help to instil awe. For example, scientists who replicate an experiment often faithfully stick to the minutiae of experimental design.
Indeed, according to the philosopher Nicholas Shea:

There may be no good reason for using 10 ml rather than 20 or 5 ml of some solvent, say. This may just be the way it was first done, and since it worked no one has bothered to find out if the quantity could be varied. Indeed, some experiments are so tricky to get right that practitioners show an almost religious adherence to the letter of a known protocol.

Awe thus plays an important role in the day-to-day work of scientists, which Kuhn called 'normal science', when it is business as usual and scientists are tweaking, rather than changing, their views. But, as I suggested at the outset, awe is especially important in revolutionary science, when scientists are grappling for new ideas and new concepts. Here, ritualistic practices might be only of limited help, but a radical reorientation is needed.

Next to ritual, there is a second way in which we can cultivate awe. We can experience it vicariously, by reading the writings of others. As the philosopher Edmund Burke, who in 1757 wrote a seminal work on the sublime, remarked:

[T]here are many things of a very affecting nature, which can seldom occur in the reality, but the words that represent them often do, and thus they have an opportunity of making a deep impression and of taking root in the mind, whilst the idea of the reality was transient …

This is relevant for science, because scientific theories often encompass things we cannot directly experience, so-called scientific unobservables: electrons, the early universe, dinosaurs and Neanderthals are examples. How can scientists come around to accepting such unobservables, if proof for them can never be definite?

The psychologist Benjamin Sylvester Bradley has argued that Darwin's *Origin of Species* was successful in establishing a new paradigm in part because it relied on a Romantic or Kantian notion of the sublime. While Darwin's book was not the first to use evolutionary theory to explain how new species came into existence, his work was an unusual combination of scientific rigour and poetic reflection on nature's vastness and complexity. In it, Darwin also frequently mentions our lack of knowledge, our difficulty imagining the vast timespans under which evolution happens, which are all elicitors of awe. For example:

Professor Ramsay has published an account of a downthrow in Anglesea of 2,300 feet; and he informs me that he fully believes there is one in Merionethshire of 12,000 feet; yet in these cases there is nothing on the surface to show such prodigious movements; the pile of rocks on the one or other side having been smoothly swept away. The consideration of these facts impresses my mind almost in the same manner as does the vain endeavour to grapple with the idea of eternity.

Awe increases our tolerance for uncertainty and opens our receptivity to new and unusual ideas, which are crucial for paradigm change. Mary Somerville's *On the Connexion of the Physical Sciences* (1834) was a highly popular synthesis of science of this time, and also anticipated novel ideas such as the existence of Neptune due to orbital anomalies long before it was discovered by telescope, and the existence of exoplanets and other not yet detected astronomical matter. Frequently, Somerville appealed to the readers' sense of awe, as here:

So numerous are the objects which meet our view in the heavens, that we cannot imagine a part of space where some light would not strike the eye; innumerable stars, thousands of double and multiple systems, clusters in one blaze with their tens of thousands of stars, and the nebulæ amazing us by the strangeness of their forms and the incomprehensibility of their nature, till at last, from the limit of our senses, even these thin and airy phantoms vanish in the distance. If such remote bodies shone by reflected light, we should be unconscious of their existence. Each star must then be a sun, and may be presumed to have its system of planets, satellites, and comets, like our own; and, for aught we know, myriads of bodies may be wandering in space unseen by us, of whose nature we can form no idea, and still less of the part they perform in the economy of the universe.

This blending of the poetic and the scientific is what Kathryn Neeley in her biography of Somerville called the scientific sublime, 'the capacity of the vision of nature revealed through science to summon forth the same sense of majesty and power that human beings feel in the presence of God.'

Awe is required not only for the day-to-day working of science, but is also crucial to help reorient scientists' thinking in times of paradigm change. It provides constant emotional motivation for scientists to continue their work, and it instils openness to scientific ideas in the public. While precision and rigour are important, the emotional drive of awe is what matters – it might be, as Heschel speculated, our only path to knowledge and wisdom.